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Approved for EDF by: A. MARECHAL		Approved for AREVA by: G. CRAIG
Name/Initials <i>A. J. C. Marelal</i> Date 29-10-2012		Name/Initials  Date 29-10-2012

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#### **For information address:**



AREVA NP SAS  
Tour AREVA  
92084 Paris La Défense Cedex  
France



EDF  
Division Ingénierie Nucléaire  
Centre National d'Équipement Nucléaire  
165-173, avenue Pierre Brossolette  
BP900  
92542 Montrouge  
France

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## SUB-CHAPTER 5.5 – REACTOR CHEMISTRY

This sub-chapter provides a description of the primary and secondary side chemistry, including the chemistry of auxiliary systems. The choice of materials for primary and secondary systems is a key parameter to ensure the safe operation of the unit. Taking into account this choice, the chemistry is optimised to ensure the integrity of materials and to reduce radiation fields.

The main chemistry parameters are described and justified in this sub-chapter, including the design optimisation which provides the means to achieve the objectives of nuclear safety, radiation protection, material and equipment integrity, minimisation of environmental impact, hazard protection (flammability risk) and operational performance.

### 1. PRIMARY AND AUXILIARY SYSTEMS WATER CHEMISTRY

This sub-chapter deals with the water chemistry of the primary and auxiliary systems. From PCSR Chapters 6 and 9, there are five main groups of auxiliary systems.

- Primary Auxiliary, Fuel Handling and Storage Systems: RCV [CVCS], REA [RBWMS], REN [NSS], TEP [CSTS], PTR [FPPS].
- Water Systems: RRI [CCWS], SEC [ESWS], SRU [UCWS], CFI [CWFS], SFI (raw water filtration system), SED.
- Heating, Ventilation and Air Conditioning Systems : HVAC systems
- Supporting Systems: Fire Protection systems, Diesel Generators, Compressed air systems, Communication Systems, Lighting, Gas distribution and storage,
- Safeguard Systems: Containment systems (EDE [AVS], ETY [CGCS], Leak rate control and testing [EPP], EVU [CHRS]); RIS [SIS], ASG [EFWS], RBS [EBS], VDA [MSRT].

The auxiliary systems that play a role in the chemistry-radiochemistry of the primary coolant, or contribute to achieving the claims associated with the primary circuit, are considered within the scope of this sub-chapter, i.e. RCV [CVCS], REA [RBWMS], REN [NSS], TEP [CSTS], PTR [FPPS], RRI [CCWS], EVU [CHRS], RIS [SIS], RBS [EBS]. It should be noted that the HVAC systems and the secondary systems (ASG [EFWS], VDA [MSRT]) are also affected by chemistry or radiochemistry issues but they are related to airborne and steam activity management respectively.

#### 1.1. CLAIMS AND ASSOCIATED ARGUMENTS

The claims associated with the management of the chemistry of the primary coolant and auxiliary systems are:

- To contribute to achieving the fundamental safety functions;
- To maintain the integrity of the first barrier (the fuel cladding);

- To maintain the integrity of the second barrier (the reactor coolant pressure boundary);
- To contribute to the reduction of radiation doses according to the ALARP approach;
- To ensure the optimal representative sampling;
- To contribute to limiting the impact on the environment;
- To improve plant performance: Plant Operating Availability.

The above claims are justified by several arguments developed in the following sections of this sub-chapter. In some cases, an argument will support several different claims. However, under certain conditions, the chemistry parameters that are optimum for one claim can have an adverse impact on the achievement of another claim.

Due to the multiplicity of chemistry and radiochemistry parameters and their variation throughout the different phases of the reactor cycles (power operation, shutdown, start-up, transient periods, boration, etc.), an overall balance must be performed in order to identify the advantages and drawbacks of each solution. The UK EPR primary chemistry strategy has been defined taking into account all the different considerations [Ref-1].

The claims are summarised in the table below, with a link to the section where they are described.

Claim	Arguments	Section describing the claim
Safety	Boron Management	1.1.1.1
	Flammability risk	1.1.1.2
	Initial conditions for radiological consequences studies during accidents	1.1.1
	Control of the nuclear island containment barrier integrity in the short term	1.1.2.2
First barrier Integrity	Limiting CRUD deposition by pH control, zinc injection, limitation of impurities and choice of gadolinium as burnable poison	1.1.2.1
	Limiting corrosion risk by fuel cladding material selection and fuel failure monitoring	1.1.2.2
Second barrier Integrity	Good performance of Alloy 690 under primary coolant conditions and monitoring of primary to secondary side leaks	1.1.3
Radiation Field Optimisation	pH optimisation (Lithium / boron concentrations)	1.1.4.2
	Zinc injection	1.1.4.3
	Control of H <sub>2</sub> concentration	1.1.4.4
	O <sub>2</sub> concentration elimination improvement during boron recycling	1.1.4.5
	Material selection and fabrication processes	1.1.4.1
	Purification optimisation	1.1.4.6
	Transient periods optimisation	1.1.4.7
Measurement Accuracy	REN [NSS] design	1.1.5
	Measurement frequencies	1.1.5
Limit Impact on Environment	Zinc injection	1.1.6
	Tritium management	1.1.6
	Carbon management	1.1.6
	Noble gas management	1.1.6
	Iodine management	1.1.6
	Fissile material Incorporation	1.1.6
Operating unit availability	Axial Offset Anomaly (AOA) management	1.1.7
	Fuel failure management	1.1.7
	RCP [RCS] material resistant to corrosion	1.1.7 & 1.1.3

**1.1.1. Contribution to Safety Functions**

The chemistry of the primary and auxiliary circuits contributes to the safety of the plant during normal operation through the management of:

- The boron concentration required for neutronic reactivity control in the RCP [RCS] and for boron management in the auxiliary borated systems (RIS [SIS], IRWST, RBS [EBS]);
- The hydrogen and oxygen concentration in the primary circuit, as well as in the gas phases of tanks, which are connected with the primary circuit (RPE [NVDS], TEP [CSTS], pressuriser, RCV [CVCS]) in order to ensure the absence of any flammability risk due to H<sub>2</sub>/O<sub>2</sub> mixtures;
- The total gas activity during full power operation in order to prevent the potential Eq. I-131 activity limit spike during transient periods after RIS-RA [SIS-RHRS] connection in order to prevent PCC radiological consequences during a unit outage. The limiting iodine activity is minimised in order to limit the radiological consequences during accidents [Ref-1] [Ref-2].
- Iodine mitigation by means of sodium hydroxide storage and injection by the EVU [CHRS] system in order to mitigate any radiological consequences.

**1.1.1.1. Reactivity Control: Boron Concentration Management**

The table below summarises the safety parameters for boron control including the systems concerned, the Standard Reactor State and the objective of the control of each parameter.

System (with control of Enriched Boron Concentration) Parameter	Standard Reactor State (Operating Conditions)	Safety Criteria
RCP [RCS]	A and E  (full power operation, normal shutdown on the steam generator (SG), and refuelling outage)	Core reactivity control
Spent fuel pool	A to F  (Reactor at-Power to Reactor Unloaded)	PCC studies Initial conditions during refuelling outage and criticality baseline in other states
IRWST	A to E  (Reactor at Power to Refuelling Outage)	Availability of a PCC mitigation means
RBS [EBS]	A to E  (Reactor at Power to Refuelling Outage)	Availability of a PCC mitigation means
RIS [SIS] accumulators	A and B (P > 70 bar) (Reactor at-Power, Normal Shutdown on SG P > 70 bar)	Availability of a PCC mitigation means

**Safety Parameters associated with Boron Control [Ref-1].**

For the UK EPR, Enriched Boric Acid (EBA) has been selected due to the high B-10 concentration that is required by the fuel management cycle (high enrichment of up to 5% U-235, long fuel cycles of up to 22 months) together with pH optimisation. The use of natural boron (~19.9% B-10) has been considered unsuitable for the UK EPR due to several concerns:

- Increase of boron concentration at the beginning of the cycle resulting in a low pH and an increase in the risk of flux neutron deformations (Axial Offset Anomaly phenomenon);
- Increase in the volume capacities of systems (equipment) containing borated water (REA [RBWMS], RBS [EBS], TEP [CSTS]);
- Limitation of the boric acid crystallisation risk. The boron concentration is limited to 7000 mg/kg; high boron concentrations (exceeding the values of safety studies detailed in Chapter 14) can lead to piping or component obstruction at low temperatures.

The use of EBA requires specific equipment and controls which will ensure effective boron concentration monitoring and application of corrective actions under all conditions. These different measures, taken into account in the UK EPR design, are described in section 1.2.

#### **1.1.1.2. Flammability Risk Control: Hydrogen and Oxygen Concentration Management**

The risk of flammable mixtures is managed by comprehensive control of the hydrogen and oxygen concentration during all phases of reactor operation (from states A to F). This control is ensured in the UK EPR by several complementary measures:

- Continuous sweeping with N<sub>2</sub> of the volumes connected to the RCP [RCS] by the TEG [GWPS];
- Use of H<sub>2</sub>/O<sub>2</sub> recombiner in the TEG [GWPS];
- Shutdown procedure improvements including:
  - the use of mechanical degassing: TEP4 [CDS] degasifier, pressuriser to RPE [NVDS] degassing line;
  - hydrazine injection in order to eliminate the potential oxygen ingress following the RIS/RRA [SIS/RHRS] connection;
  - the possibility of chemical dehydrogenation application enabling the fast elimination of residual hydrogen;
- Start-up procedure improvements including:
  - the use of TEP4 [CDS] degasifier;
  - hydrazine injection to ensure oxygen removal.

Section 1.2 describes the application of the different practices and provides the necessary confirmation to ensure the absence of any H<sub>2</sub>/O<sub>2</sub> risk.



### 1.1.2. Integrity of First Barrier

To ensure the integrity of the first barrier, the fuel cladding, it is important to limit the potential for fuel cladding failures and activity release through the defects into the primary coolant.

The causes leading to the onset of cladding defects can be linked to several phenomena, including fretting, debris, manufacturing, general corrosion, hydriding process, CRUD<sup>1</sup> corrosion, etc. Therefore, the primary coolant chemistry cannot be considered as the only way to improve the fuel performance but it can play an essential role in limiting corrosion failures and defect degradation.

The UK EPR chemistry has been defined taking into account the necessary arguments for ensuring the limitation of CRUD deposition and cladding corrosion.

#### 1.1.2.1. CRUD Deposition Limitation

CRUD deposition on fuel assemblies can first lead to the Axial Offset Anomaly (AOA) phenomenon also referred to as the CRUD Induced Power Shift (CIPS) phenomenon. AOA occurs when boron concentrates in corrosion product deposits (CRUD), on the upper spans of fuel assemblies undergoing sub-cooled nucleate boiling, causing a reduction in neutron flux. Secondly, CRUD deposition can produce cladding corrosion and induce the onset of defects in the presence of thick CRUD or with a high lithium concentration deposit. This type of failure is called CILC (Corrosion Induced Localised Corrosion).

The arguments to ensure the limitation of CRUD deposition in the UK EPR are:

#### pH control

The pH management has been selected in order to:

- Minimise the general corrosion of materials;
- Limit the corrosion product transfer between the ex-core zones and core regions;
- Limit deposition on the core.

The evidence presented in section 1.2 leads to the conclusion that the optimal pH programme for the UK EPR consists of a constant high pH<sub>300°C</sub> of 7.2. This value is the input requirement to determine the lithium-boron coordination during the fuel cycle. However, regarding the fuel performance, there are two additional prerequisites that the pH programme must comply with:

- Limitation of lithium concentration to prevent cladding corrosion. According to the statements presented in section 1.2 the limit value of lithium concentration is fixed at 4 mg/kg at the beginning of the cycle.
- Limitation of the boron concentration to prevent borate deposition on the fuel cladding and the subsequent neutron flux distortion due to the neutron-absorbing characteristics of boron. It should be noted that the use of EBA is necessary for the UK EPR reactor in order to reach a pH<sub>300°C</sub> of 7.2 while complying with the limit value of lithium concentration (4 mg/kg).

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<sup>1</sup> Chalk River Unidentified Deposits ( namely, corrosion products in general)

### Zinc injection application

The addition of zinc in the primary circuit presents relative advantages and disadvantages for different issues (see section 1.2.3). In particular, the positive effect of zinc on CRUD deposition limitation is justified by:

- Limitation of general corrosion of primary circuit material (Alloys 690 and Stainless Steel) leading to a decrease in the source term likely to be deposited on the fuel assemblies;
- Reduction of CRUD residential time on the external surface of fuel cladding rods;
- Uniform CRUD distribution on fuel cladding.

Section 1.2 provides the quantitative and qualitative evidence for zinc injection actions with respect to the fuel cladding along with the conditions of application.

### Impurities limitations

The impurities controlled and limited in the primary circuit of the UK EPR with respect to their impact on CRUD deposition are:

- Calcium, magnesium, aluminium;
- Silica;
- Suspended solid;
- Nickel.

### Gadolinium (see section 6.2.1.3.1 of Sub-chapter 6.3 of the PCER)

Gadolinium oxide has been selected as the burnable poison for the control of reactivity and is incorporated into the design of burnable poison fuel rods. This poison consists of mixing gadolinium oxide ( $Gd_2O_3$ ) with the  $UO_2$  in the pellets of some of the fuel rods.

The use of gadolinium contributes to reducing the boron concentration in the primary circuit and thus the potential borate precipitation on the fuel assemblies.

#### **1.1.2.2. Cladding Corrosion Limitation**

Fuel failures due to cladding corrosion are limited and controlled in the UK EPR by:

##### **Alloy selection**

The new Zircaloy-M5 alloy which will be used in the fuel cladding for the UK EPR has significantly reduced corrosion rates compared to zirconium alloys previously used and thus will support the achievement of higher burn-up rates.

Furthermore, the use of Zircaloy-M5 cladding material will allow the higher lithium concentration in the primary circuit required to obtain a  $pH_{300^{\circ}C}$  of 7.2, and will ensure high burn-up (around 65 GWd/t) (see PCER Sub-chapter 8.2, section 3.2.1).

**Fuel failure monitoring**

Fission product monitoring during the fuel cycle is based on several criteria to ensure:

- The fuel defect onset detection by the use of Xe-133 and Xe-133/Xe-135 as the main indicators;
- The characterisation of failed rods by the use of Cs-134/Cs-137 and linear power to determine the irradiation cycle and localisation;
- The degradation evaluation concerning the potential risks (alpha/iodine) by the use of I-134 activity.

The radiochemistry specifications have taken into account the relative benefits and disadvantages of each parameter, the expected values, the limit values in order to avoid fuel failure degradation, together with the potential impact on the global integrity of the first barrier.

**1.1.3. Integrity of the Second Barrier**

The main structural materials of the primary circuit of the UK EPR reactor are austenitic stainless steel and Alloy 690TT as well as their associated weld metals.

Alloy 690TT and its compatible weld metals have been introduced to eliminate the generic problem of stress corrosion cracking (often known as Primary Water Stress Corrosion Cracking, PWSCC) encountered in Alloy 600 and its weld metals in PWR primary water service. As Alloy 690TT is more resistant to PWSCC than Alloy 600, the risks of cracking are very low: Alloy 690TT has not cracked after up to 20 years in PWR primary service and has resisted cracking in more severe laboratory tests [Ref-1].

The materials selected for the UK EPR (non-sensitive stainless steel and Alloy 690TT) have been chosen for their excellent corrosion resistance. However, although the materials of the UK EPR reactor are optimised to limit as far as possible the risks of corrosion, it is still important to limit the impurity concentrations as a precautionary measure. The normal control of impurities (chlorides, fluorides, oxygen, sulphate, and sodium) will be performed as preventive measurements and the Nitrogen-16 KRT [PRMS] monitoring enables the detection of any primary or secondary SG leakage.

Containment of radioactive waste is provided by different systems, notably the TEG [GWPS] and the RPE [NVDS] systems which form part of the third containment barrier. These systems facilitate management of liquid and gaseous radioactive effluent during normal operation and during fault conditions. In particular, the Nuclear Island Vent/Drain Systems (RPE [NVDS]) contributes to the containment of radioactive substances in the nuclear island buildings and to the limitation of releases into the environment:

- During normal conditions, by monitoring of leakages, selective recovery of effluent, and optimisation of effluent discharge versus effluent treatment; and
- During abnormal conditions by delaying the treatment of high active effluent (re-injection of leaks from the RIS [SIS] system in the Reactor Building).

Accordingly, the RPE [NVDS] system is utilised to effectively cope with leaks from the primary system during normal operation (see PCSR Sub-chapter 11.4).

#### 1.1.4. Radiation Field Optimisation

The definition of source terms and specific activities is detailed in Sub-chapter 11.1. This source term is used as a design parameter for EPR buildings, systems and shielding provisions; the values are conservative and come from spectrometric measurements in the N4 units. The primary system inventory of radionuclides which may have an effect on the protection of workers against ionising radiation is given in Sub-chapter 12.2 - Table 1 for normal operation, and in Sub-chapter 12.2 - Table 2 for power transients (load reduction for fission products and oxygenation peak for corrosion products).

This section describes the ALARP approach introduced in the UK EPR in terms of materials and chemistry which contribute to minimising the source term, and thus minimise the radiation field; [Ref-1] [Ref-2] [Ref-3].

During outage maintenance, personnel exposure is mainly caused by activated corrosion product deposits, which account for the major contribution to dose rates in the vicinity of systems and components. Furthermore, the accumulative contamination in the circuits will have an impact on decommissioning operations. The reduction of contamination is therefore of prime importance.

Accumulation of activated corrosion products on ex-core surfaces is the main cause of build-up of radiation fields. The mechanisms associated with this process are:

- Corrosion product release into the primary coolant from ex-core surfaces (in particular by the SG due to its surface);
- Transfer of corrosion products released into the primary coolant to the core region;
- Deposition of corrosion product on the fuel cladding assemblies;
- Activation of corrosion product by exposure to neutron flux;
- Transfer of some of the corrosion products activated in the core to the ex-core surface (loops, steam generator);
- Incorporation of corrosion products activated in ex-core oxides.

Each of these steps is influenced by the primary coolant chemistry. The modification of chemical parameters during the different phases of a fuel cycle, shutdown, and start-up can have an important effect (positive or negative) on the ex-core radioactivity.

For the UK EPR several complementary actions are applied in order to optimise each one of the mentioned steps.

##### 1.1.4.1. Material Selection

The material selection mainly has an effect on the first step of the contamination processes. Accordingly, material selection has been performed taking into account:

- The composition of materials;
- The mechanisms of corrosion and wear of the RCP [RCS] and auxiliary systems components.

The selection of material has been based on the following principles:

- Cobalt reduction is ALARP due to
  - the replacement of Stellite™ material by cobalt-free material;
  - the use of low cobalt material specification (principally Alloy 690TT and stainless steel)
- Antimony reduction due to:
  - the elimination of antimony in the auxiliary systems of the UK EPR;
  - the use of a secondary rod source with a limit on exposure to primary coolant and an improved design limiting the risk of clad diametral bending.
- Silver reduction due to:
  - the use of graphite seals or welded type design of piping instead of flange type designs of piping systems;
  - the use of nitride coating on rod controls.
- The use of materials with low release rates, such as stainless steels or nickel based Alloys 690TT, due to the optimisation of fabrication processes (i.e., SG Alloy 690 tubing manufacturing).

Furthermore, the reactor design includes neutron shielding. This shielding reduces the activation of materials and thereby facilitates the clean-up of the structures while reducing the volume of active waste. The principal reactor core shielding components are:

- The neutron shield (also referred to as 'heavy reflector', see Sub-chapter 4.3) surrounding the core, made of a dozen circular elements joined together by vertical tie-rods;
- The slab positioned above the vessel, comprised of multiple removable concrete sections.

#### **1.1.4.2. Primary coolant pH Control**

The pH strategy for the UK EPR contributes essentially to limit:

- Corrosion product release from ex-core surfaces;
- The transfer of corrosion products between the ex-core surfaces and the core region (and inversely).

These positive effects are mainly due to the influence of pH on the solubility of corrosion products. A primary coolant  $\text{pH}_{300^\circ\text{C}}$  is selected in order to obtain minimal corrosion product solubility (minimisation of the phenomena of transfer and deposition) and to obtain as much as possible a positive slope of metal solubility (solubility increase with temperature increase) in the core (limitation of the deposit formation and activation in the core).

The evaluation of the evidence provided in section 1.2.2 justifies the selection of a constant  $\text{pH}_{300^{\circ}\text{C}}$  of 7.2 for the UK EPR. This pH value is the input requirement to determine the boron–lithium coordination during the cycle as described in section 1.2.

#### 1.1.4.3. Zinc Injection Application in the Primary Coolant

Zinc injection has several positive effects on the build-up of radiation fields:

- Source term reduction and corrosion product release due to the general corrosion diminution of the material present in the primary circuit;
- Activation reduction due to the decrease of residence time of CRUD deposited on fuel cladding;
- Incorporation of cobalt reduction due to the inhibition and replacement of cobalt in the ex-core surfaces reducing the cobalt contamination (origin of 90% of dose integrated by the operator).

Based on the evidence provided in section 1.2.3, the zinc injection programme has been defined with a expected zinc range concentration of  $5 \mu\text{g}/\text{kg} < [\text{Zn}]_{\text{measured}} < 15 \mu\text{g}/\text{kg}$  (target concentration of  $10 \mu\text{g}/\text{kg}$ ).

#### 1.1.4.4. H<sub>2</sub> Control in the Primary Coolant

Hydrogen is added in the primary coolant water in order to maintain a reducing environment by limiting radiolytic decomposition of water (oxygen and oxidising species source).

Due to the hydrogen action on the stability and the solubility of corrosion products, it also has an influence on the contamination of out-of-core surfaces. The hydrogen concentration is based on the solubility control of nickel and ferrites.

According to the evidence presented in section 1.2.4, the optimal H<sub>2</sub> concentration range is  $17 < \text{H}_2 < 50 \text{ cm}^3 \text{ (STP)}/\text{kg}$ .

#### 1.1.4.5. O<sub>2</sub> Control in the Primary Coolant and Auxiliary Systems

Corrosion product reduction has been enhanced for the UK EPR due to improved elimination of the dissolved oxygen during boron recycling by:

- Evaporation and degassing via the TEP3/5/6 [CTS];
- On-line control of oxygen in the TEP [CSTS]
- REA [RBWMS] tanks under nitrogen atmosphere due to the gaseous effluent treatment system (TEG [GWPS]); and
- Oxygen reaction with hydrogen to form water vapour via the catalyst carried out in the TEG [GWPS] recombiner.

#### 1.1.4.6. Purification Optimisation

In order to maintain low levels of impurities in the primary circuit and auxiliary circuits such as the TEP [CSTS] and REA [RBWMS] boric acid make up tanks, the UK EPR coolant must be purified at optimum conditions through the use of demineralisers and filters. The purification function is ensured with:

- RCV [CVCS] purification station at a nominal flow rate of 36 t/h at power operation (maximum 72 t/h during shutdown and start-up);
- TEP [CSTS] purification;
- Fuel pool cooling and purification system operation (PTR [FPCS]).

Section 1.2.7 provides the confirmation that the optimum UK EPR primary circuit conditions are achieved.

#### 1.1.4.7. Transient Period Optimisation

Transient periods are characterised by physicochemical conditions of the primary coolant which are not completely stable (pH, redox potential, temperature, pressure) and with potential operating state modifications (flow rates, rod variations, power transients). For this reason, the actions undertaken during transient periods have been robustly determined with respect to primary circuit contamination. The following phases have been improved for the UK EPR:

- **Hot Functional Tests:** the chemistry conditions during this phase of start-up are optimised in order to passivate the surfaces of the steam generators permitting reduction of the nickel source term.
- **Shutdown and Start-up:** the procedures applied during shutdown include:
  - H<sub>2</sub> concentration strategy;
  - iodine mitigation;
  - antimony mitigation (in case of unexpected pollution);
  - oxygen mitigation;
  - fission product control;
  - corrosion product control;
  - CRUD burst mitigation.

#### 1.1.4.8. Iodine and Alpha Risks

The importance of limiting iodine and actinides release into the primary coolant with respect to radiation optimisation is explained by the following:

- Iodine is one of the most important fission products, in terms of nuclear reactor safety, due to its high fission yield, significant radiobiological hazard, and potential volatility. Taking into account the half-life of some of these isotopes (I-129 with a half-life of 15.7 million years) and its ability to be concentrated in the thyroid gland, the iodine environmental and biological risk must be limited during the different phases of operation. For the UK EPR, the measures taken to control the iodine consequences are:
  - to specify iodine activity limits via the Eq. I-131 in steady operation;
  - to specify iodine activity via the Eq. I-131 limit during transient periods in order to comply with the dose limits in the environment;
  - to request the monitoring of I-131 during power variations at shutdown in order to avoid a level of activity in the primary coolant leading to containment contamination during reactor pressure vessel head removal (head lift after shutdown);
  - to adapt the primary coolant chemistry to limit the iodine adsorption and/or its volatility;
  - to include specific iodine filters in the different systems.
- The fissile material disseminated contributes to increase the contamination of ex-core surfaces, and the absence of alpha emitters in the effluent must be ensured under all circumstances. For the UK EPR, the measures taken to control the fissile material dissemination are:
  - to specify a limit for I-134 activity;
  - to carry out alpha activity and spectrometry alpha measurements.

#### **1.1.4.9. Tritium Management**

The radiation emitted by the pure beta emitting radionuclides such as tritium has sufficiently low energy that it can be stopped by the structures designed to protect against gamma emitting radionuclides and is not taken into account in the contribution to the radiation field. However, tritium is mentioned here as tritium activity feedback has been extensively analysed within GDA in order to define the best practices to reduce the tritium releases into the environment (section 1.1.6) and the operator dose. The proposed limits and supporting calculations will be completed according to current progress for this important programme of management.

#### **1.1.5. Measurement Accuracy**

Primary and auxiliary circuit monitoring is ensured by the REN [NSS] whose design has been established as a function of:

- Parameters to be monitored:
  - **chemistry parameters:** boron, hydrogen, oxygen, nitrogen, lithium, zinc, nickel, silica, calcium, aluminium, magnesium, sulphates, chlorides, fluorides, sodium;



- **radiochemistry parameters:** fission products, activated corrosion products, actinides, tritium, carbon-14;
- soluble and insoluble separation.
- The available techniques for the monitoring of chemistry and radiochemistry parameters soluble, gas and particulate phase;
- The frequency of measurements established by the chemistry and radiochemistry specifications according to the phases of operation and the plant operating conditions (in presence of fuel failures, pollutions, etc.).

Measurement accuracy is ensured due to the selection of the location of sampling lines and the location of system components placed to facilitate the maintenance and calibration during plant operation.

Furthermore, for the UK EPR a number of key safety features have been incorporated in order to protect the operators during sample collection.

#### **1.1.6. Limit Impact on the Environment**

The primary coolant chemistry for the UK EPR has been defined taking into account the environmental impact. This is supported by the following arguments:

- Zinc injection application enabling reduction of the source term and hence the solid waste;
- Tritium management based on good practice application and proposed limits in order to anticipate the actions required to prevent of tritium release; and the use of lithium hydroxide isotopically enriched in lithium-7.
- Carbon management due to an extensive study carried out for the UK EPR to determine the potential sources of carbon and define the carbon fate (organic, insoluble, gas);
- Noble gas management based on:
  - limitation of activity in  $\Sigma$ Gas and Xe-133 according to specifications during power operation and shutdown;
  - incorporation of delay beds in the TEG [GWPS].
- Iodine management based on:
  - limitation of activity in Eq. I-131 according to specifications during power operation and shutdowns;
  - incorporation of specific iodine filters in the applicable systems;
  - primary coolant chemistry adaptation during shutdown in order to minimise the iodine volatility.

- Fissile material management based on:
  - limitation of activity in I-134 during power operation;
  - alpha activity measurement in primary coolant and wastes;
  - thermodynamic calculations to improve the chemical primary conditions in order to better purify the actinides (particle retention, solubilisation).

Primary discharge management is based on the operational functions of the RPE [NVDS], which are:

- Selective recovery of all the liquid waste produced both inside and outside the containment and a part of the gaseous waste in the reactor building. The different categories of liquid and gaseous effluents produced by RCP [RCS] and the auxiliary systems in the nuclear island are defined according to their appropriate processing mode.
- Routing effluents to the associated storage and treatment facilities prior to monitoring and discharge.
- Leak detection by collecting the effluents in tanks and sumps.

In this respect, the RPE [NVDS] contributes to compliance with the authorised discharge limits for liquid and gaseous waste (see PCSR Sub-chapter 11.4).

#### **1.1.7. Operating Unit Availability**

The items which could have an impact on reactor operation are:

- The development of Axial Offset Anomalies: this phenomenon can lead to power reductions and unplanned shutdowns;
- Corrosion on RCP [RCS] materials

For the UK EPR the following measures have been taken to manage the AOA and fuel failure management:

- chemistry and radiochemistry monitoring: the optimisation of the corrosion product monitoring during the cycles enables early alerts regarding the increase of particulate species and the possible increase of CRUD deposition on fuel assemblies [Ref-1]. Moreover, during the transient periods, the online monitoring of boron and lithium facilitates the detection of lithium releases from potential borate deposited on un-expected CRUD and anticipates the possible consequential neutron flux transient;
- neutron monitoring: The flux map analysis carried out during periodic tests reveals the presence of local deformations and anticipate any core deformation;
- predictive estimation: calculations with neutron and thermo-hydraulic codes coupled with CRUD models.

- fission product monitoring based on activity measurement in the primary coolant. These analyses are adapted to detect fuel cladding defects and their characteristics during the fuel cycle allowing the actions during shutdown to be anticipated: sipping test degassing, chemistry conditions adaptation;
- application of shutdown procedures in order to improve fission product degassing and purification;
- compliance with the requirements of radiochemistry specifications;
- support from modelling evaluations [Ref-1].

For the UK EPR the choice of RCP [RCS] grade materials (see section 1.1.3) helps to minimise the risk of corrosion and thus improves the availability of the unit.

**1.2. EVIDENCE SUPPORTING THE OPTIONS RETAINED FOR UK EPR**

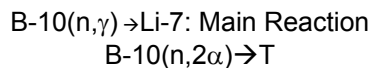
The justification principles which support the various arguments are first described in order to underline the options selected for UK EPR, their operating consequences, and motivations. The details of the justification are provided in the documents referenced herein.

**1.2.1. Evidence supporting the Boron Management Strategy**

The boron management strategy has been established following the steps outlined below:

Additive selection

According to Sub-chapter 4.2, the soluble boron in the primary coolant contributes<sup>2</sup> to reactivity control due to the high neutron cross-section of the isotope B-10 by the reactions:



This B-10 is present in natural boron in atomic proportions of about 19.6% and 20.2% depending on its geological origin. This amount of B-10 from natural boron determines the total quantity of boron quantity needing to be injected, according to the core requirements. The dominant isotope from natural boron B-11 does not have neutron poison properties.

Boron is injected into the primary coolant as boric acid (H<sub>3</sub>BO<sub>3</sub>) which is a light acid allowing the target pH (section 1.2.1.2) to be established.

Fuel management cycle developments (enrichment, cycle length, power, etc.) lead to a higher quantity of natural boron than is currently used in operating PWRs. For this reason, the selection of Enriched Boric Acid (EBA) corresponds to a design choice taken into account for the UK EPR reactor design and operating conditions:

- Extra Boration System (RBS [EBS]) sizing, because the injection of a sufficient quantity of anti-reactivity (boric acid) in a given time is necessary to meet safety conditions in case of an accident;

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<sup>2</sup> Gadolinium in the form of burnable rods is used as an additional neutron poison to establish the required initial core reactivity and power distribution.

- Borated capacity dimensions (REA [RBWMS] boron, IRWST, RBS [EBS] tank, RIS [SIS] accumulator, Spent Fuel Pool);
- Boron crystallisation risk prevented by temperature control of the room(s) and associated circuits [Ref-1];
- Lithium concentrations at the beginning of the cycle in order to reach, as soon as possible, a constant pH of 7.2.

#### Enrichment strategy

The enrichment strategy should be established taking into account operator constraints. Accordingly, the specific enrichment strategy will be determined by the operator. However, the initial conditioning has been defined for the reference design of the UK EPR; the first conditioning will be directly with EBA with an expected target enrichment of 37% atomic.

Concerning isotopic adjustment during, or at the end of, the cycle (systematically prior to any refuelling shutdown), the strategy is “direct re-enrichment” in the REA [RBWMS] boron make-up system with a solution of High Enriched EBA (> 95% atomic).

In the evaluation of analysis risks, the use of different types of boric acid has been considered as a possible source of human error with potential consequences for plant operation. Furthermore, the different uncertainties identified in the boron management strategy (linked to measurement, monitoring, solution preparation, calculations) must be taken into account in the isotopic nominal concentration of enriched boric acid provided by the suppliers. The specific margins for consideration will be detailed in plant operating procedures.

#### EBA strategy monitoring

The strategy established enables the use of EBA without any resulting safety concerns, but does lead to some additional operations for chemistry staff. In order to make these activities easier and to reduce the potential for human error, the following tools are provided:

- Identification of control parameters and monitoring tools, specifically boron concentration has to be monitored by the measurement of three parameters:
  - total boron concentration: a necessary parameter for pH determination, Li-B programme verification and boron crystallisation assessment risk;
  - B-10 concentration for neutron reactivity control;
  - change in isotopic percent in boron B-10: enabling the boron depletion in the systems connected to the primary coolant to be monitored and corrected.

The table below provides the measurement techniques and the formula used for regular calculations.

Parameter	Objective of monitoring	Analytical Measurement	Location of measurement	Systems concerned by the measurement
Enrich.(% at)	<ul style="list-style-type: none"> <li>o Control of boron depletion</li> <li>o Control of all possible event inducing isotopic dilution (e.g. make up water)</li> </ul>	ICP/MS →provides isotopic atomic ratio $R_{ICP/MS} = B-10/B-11$	Chemistry Laboratory	<ul style="list-style-type: none"> <li>o RCP [RCS] and connected systems (PZR, RCV [CVCS], RIS/RRA [SIS/RHRS])</li> <li>o REA [RBWMS] boron</li> <li>o IRWST</li> <li>o Fuel pool</li> <li>o TEP [CSTS]</li> <li>o RBS [EBS]</li> <li>o Accumulator RIS [SIS]</li> </ul>
Cb: Total Boron Concentration (mg/kg)	<ul style="list-style-type: none"> <li>o pH control of primary circuit.</li> <li>o Control of re-crystallisation risk in auxiliary system</li> </ul>	Neutronic boron meter (systems connected to REN [NSS])	On line (continuous measurement via REN [NSS])	
		Manual Tritimetry (RCP [RCS] and auxiliary systems)	Chemistry Laboratory	
Cb10: B-10 concentration (mg/kg)	Reactivity control	Neutronic boron meter (systems connected to REN [NSS])	On line (continuous measurement via REN [NSS])	RCP [RCS]

Depletion simulations:

The phenomenon of B-10 depletion is the consequence of the neutronic reactions in the core. During a cycle, B-10 is progressively consumed mainly by the reaction  $B-10(n,\gamma) Li-7$ . The progressive reduction of B-10 is a phenomenon called depletion and it requires adapted monitoring. The indicator selected is the Depletion Index, D, defined as:

$$D = \frac{Enrich(\%at.)_{target} - Enrich(\%at.)_t}{Enrich(\%at.)_{target} - Enrich(\%at.)_{min}}$$

Where:

- **Enrich(%at.)<sub>target</sub>**: target B-10 enrichment
- **Enrich(%at.)<sub>t</sub>**: B-10 enrichment at a time t
- **Enrich(%at.)<sub>min</sub>**: minimum admissible B-10 enrichment

This index, D, is between 0 and 1, where 0 corresponds to the absence of depletion and 1 to maximal depletion.

This index allows a comparison between the isotopic proportion measurement at a specific 't' and the minimal value admissible in exploitation.

Several simulations will be carried out for the UK EPR in order to reproduce the depletion phenomenon taking into account the different influencing factors identified: fuel management parameters and intermediate shutdown.

According to the results obtained thus far, a periodic re-enrichment process must be put in place in order to compensate for the B-10 lost.

The details of these simulations for the different scenarios identified will be provided to the utility as an operating procedure to arrange the necessary activities during a cycle and prepare the adapted amounts of additive for the re-enrichment process.

Boron concentration in auxiliary systems

The minimum-maximum boron concentrations for safety systems (RBS [EBS], IRWST, RIS [SIS] accumulators) are given in PCSR Sub-chapter 14.1. These values are calculated assuming the initial conditions of PCC safety studies and the availability of PCC mitigation means.

The table below lists the borated systems and the associated boron concentration.

Boron Concentration during normal power operation	Systems
Constant boron concentration at 7000 mg/kg	RBS [EBS] REA [RBWMS]
Variable boron concentration as a function of fuel management during full power operation	RCP [RCS] RCV [CVCS] TEP [CSTS] REN [NSS] RIS/RA [SIS/RHRS]
Constant boron concentration at Fuel Refuelling Concentration during full power operation	IRWST RIS [SIS] accumulators Fuel Pool Reactor Pool

**Identification of Borated Systems**

The design countermeasures applied for the UK EPR to ensure boron management are also listed:

- 1) The first measure applied to facilitate boron management consists of limiting human factor risks and simplifying information transmission between the measurement instruments (RCV [CVCS], REN [NSS] boron meters), the Instrumentation & Control (I&C) and the control room. For this reason, only one representative boron measurement was selected as an input to the I&C. The boron-10 concentration has been selected as the representative measurement for ensuring core reactivity control, while the total concentration of enriched boron has been selected for monitoring the crystallisation risk and determining the pH<sub>T</sub> control.

Due to this decision, the depletion of boron-10 during the cycle in the RCP [RCS], REA [RBWMS], RCV [CVCS] and TEP [CSTS] does not have any effect on the control of core reactivity or power distribution. For the UK EPR, all the measurements of boron concentration are transmitted to the control room and the I&C as boron-10 concentrations.

- 2) The second measure applied to ensure compliance with the safety requirements consists of maintaining boron concentration homogeneity in the different borated systems. The UK EPR reactor design provides the necessary means for applying re-enrichment actions:
- At the end of the cycle, the necessary amount of enriched boron can be added via the REA [RBWMS] boron train, with fresh enriched boric acid in order to compensate for isotopic depletion in the primary coolant and the connected borated systems (RCV [CVCS], REA [RBWMS], TEP [CSTS]).
  - Likewise, in order to avoid boron depletion in the IRWST, the UK EPR will contain the necessary devices and installations to adjust the isotopic ratio, prior to RCP [RCS] pool filling.
- 3) The third measure applied to ensure the correct boron concentration during the different phases of the cycle is the use of boron saturated mixed beds as a function of the burn-up and the operations performed. Different operational configurations are possible due to the design and the features provided by the coolant purification systems including RCV2 [CVCS2] and TEP2 [CPS] [Ref-2]. At the end of the cycle, boron adjustment can be performed using a third mixed bed as an anionic bed, connected in series with the main RCV2 [CVCS2] demineraliser.

### 1.2.2. Evidence supporting the Application of the UK EPR pH Programme

The UK EPR primary coolant pH programme management is associated with the following claims:

- Material integrity due to the effects on general corrosion of RCP [RCS] materials and fuel cladding corrosion.
- Radiation field due to the effect on solubility of corrosion products and consequently in the transfer of source term from the ex-core surfaces to the fuel assemblies where the activation occurs and inversely from the core to the surface of primary circuit where the activated elements are deposited.
- The Plant Operational Availability due to the influence on CRUD deposition on fuel cladding inducing AOA and/or fuel cladding failures.
- The sampling system capability due to the need to maintain the target pH during the entire cycle via the control of lithium and boron. The REN [NSS] of the UK EPR is equipped with the necessary measurement techniques and with the I&C measures to ensure the pH control.

Therefore the pH programme selected has to:

- Compensate for the potential risks associated with a low or high pH, lithium concentration and/or boron concentration;
- Take advantage of the benefits associated with a low or high pH, lithium concentration and/or boron concentration.

The table below underlines the main issues relative to the pH programme for each item (material integrity, etc.) to determine the underlying principles for specification selection.

Domain	Material Integrity	Radiation field / CRUD Management	Operational Availability
Main Issues	First Barrier Integrity: maximum lithium concentration to limit fuel cladding corrosion	Optimal pH programme, lithium concentration, boron concentration to reduce the transfer of corrosion product and CRUD deposition	Optimal pH programme, lithium concentration, boron concentration to limit AOA and CILC
	Optimal pH to reduce General Corrosion of the RCP [RCS]		

**1.2.2.1. Identification and Quantification of Evidence**

**1.2.2.1.1. Material Integrity Evidence**

According to autoclave tests, lithium hydroxide accelerates corrosion of zirconium alloys at temperatures around 300°C for concentrations of lithium greater than 8 mg/kg [Ref-2]. The tests show that in the presence of boron, dissolved in the primary circuit, the negative lithium effect on corrosion cladding is improved. However, the presence of boron can favour the lithium borate precipitation on fuel cladding.

For these reasons [Ref-2] [Ref-3], the lithium concentration is considered by fuel suppliers as a limiting factor of fuel design and a maximum lithium concentration and time of exposure are specified with regard to first barrier integrity.

Accordingly, the maximum lithium concentration selected for UK EPR has to:

- Allow the pH specified by radiation and/or CRUD claim to be achieved.
- Be in compliance with cladding alloy operating experience. To date, most of the units with cladding alloys of high Nb concentrations operate with a maximum lithium concentration ( $[Li]_{max}$ ) of 3.5 to 4 mg/kg. Experimental programmes and operational experience provide confirmation that no adverse effects regarding material behaviour have been reported for such lithium concentrations.

The influence of high lithium primary water on Stress Corrosion Cracking (SCC) for the UK EPR is not considered an issue concerning Primary Water Stress Corrosion Cracking (PWSCC) and Irradiation Assisted Stress Corrosion Cracking (IASCC) according to the laboratory test results [Ref-1].

**1.2.2.1.2. Radiation field / CRUD Management / Availability**

The optimal pH programme for the UK EPR has been selected taking into account two principles:

- Minimise the corrosion product transfer to the core:
  - the reduction of general corrosion and release corrosion rates of primary circuit surfaces;



- the reduction of corrosion product solubility in the core inlet surfaces (low temperature around 290°C).
- Minimise the corrosion product deposition in the core:
  - the reduction of the source term likely to be deposited in the core (mainly the species found in the upper regions of the assemblies where the deposition risk is higher due to the increased boiling rates);
  - the increase of corrosion product solubility in the core outlet surfaces (high temperature around 320°C).

The justifications supporting the selected values are based on:

- Empirical tests:
  - **determine the composition of deposits on ex-core surfaces**: consisting of an inner layer rich in chromium and an outer layer of mainly nickel and iron oxides.
  - **determine the composition of fuel CRUD [Ref-1] [Ref-2] [Ref-3]**: CRUD composition can vary from predominantly iron based nickel ferrite material ( $Ni_xFe_{3-x}O_4$ ) to a predominantly nickel based needle material.
  - **the pH effect on corrosion of materials**: corrosion rates and corrosion release rates are expected to decrease with increasing  $pH_T$  from 6.9 to 7.4 for Alloys 600, 690, and stainless steel. The laboratory results provide a corrosion reduction of about 5% - 7% when pH increases from 6.9 to 7.2 and 7.4. Hence the benefit decreases as the  $pH_T$  approaches a pH of 7.4.

**From the elements based on the laboratory and experimental reactors it is concluded that the optimal target pH is  $\geq 7.2$ .**

- NPP feedback [Ref-3]:
  - The positive or negative effects on radiation fields and CRUD deposition of increasing or decreasing pH are difficult to evaluate from NPP feedback due to the different conditions of operation and fuel management. Nevertheless, two important conclusions have to be considered:
    - keeping the pH constant contributes towards maintaining a stable corrosion product solubility and consequently towards preventing corrosion product transport [Ref-3];
    - ensuring a  $pH > 6.9$  is essential to prevent the AOA and CILC phenomena. The cause of AOA and/or CILC in several NPPs has been a low pH ( $pH < 6.9$ ) at the beginning of the cycle.

**The differences between a pH of 7.2 and 7.4 in terms of primary coolant activity or dose are not discriminate. However, the basis for implementation of a pH of 7.4 must take into account the possible high lithium concentration (depending on boron concentration and length of cycle).**

- Calculations:

In spite of uncertainty and gaps in knowledge internationally, the following conclusions can be drawn [Ref-2] [Ref-3]: [Ref-4]:

- The pH for the minimum solubility level of iron from magnetite ( $\text{Fe}_3\text{O}_4$ ) and from nickel ferrite ( $\text{Ni-Fe}_3\text{O}_4$ ) is in the range of 6.9 to 7.0.
- The pH for the minimum solubility level of nickel from nickel metallic and nickel oxide are obtained for a  $\text{pH}_{300^\circ\text{C}}$  of 7.6 to 8.5. These values require high lithium concentrations inducing potential risks on cladding corrosion and lithium borate deposition. Therefore, the pH optimisation is not established with regard to the nickel solubility on ex-core surfaces, but it has been considered as part of the overall approach.
- The calculations carried out reveal a decrease of about 10% of the corrosion products deposited on out of core areas applying a constant pH of 7.2 (with  $[\text{Li}]_{\text{max}} = 4 \text{ mg/kg}$ ) compared with a modified chemistry characterised by a variable pH of 6.9 to 7.2 with  $[\text{Li}]_{\text{max}} = 3.5 \text{ mg/kg}$ .

**From the elements based on calculations, it is concluded that the optimal pH is  $\geq 7.2$ .**

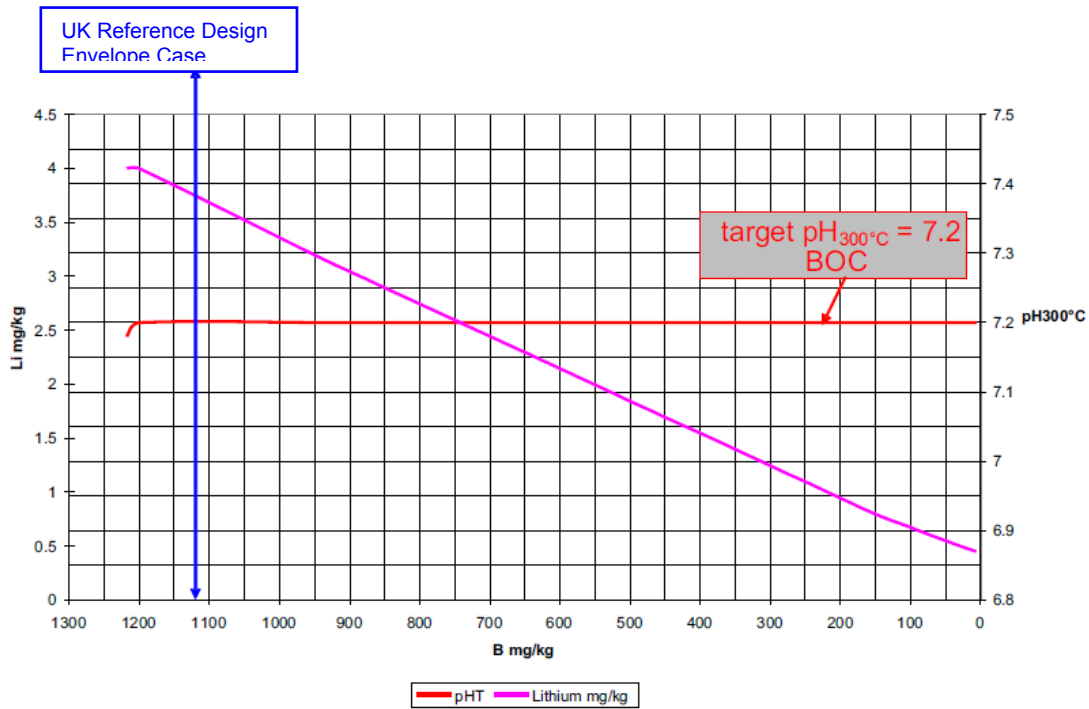
With regard to field and CRUD management, the target  $\text{pH}_{300^\circ\text{C}}$  value retained for UK EPR is  $\geq 7.2$  with a lower limit value of 6.9.

#### 1.2.2.2. pH Programme Implementation for UK EPR

##### 1.2.2.2.1. Specifications

Based on the information presented in section 1.2.1.1, the optimal pH programme selected for the UK EPR [Ref-1] primary coolant is governed by:

- A constant high temperature pH programme; with a target value of  $\text{pH}_{300^\circ\text{C}}$  of 7.2 and a lower limit value of 6.9 (see sub-section 1.2.2.1.1)
- Maximum lithium concentration ( $[\text{Li}]_{\text{max}}$ ) = 4 mg/kg at the beginning of the cycle.



**1.2.2.2.2. Lithium Injection Control**

Lithium concentration control for the UK EPR is ensured by a continuous lithium measurement in the REN [NSS] and an automatic injection performed via the RCV [CVCS] [Ref-1]. The lithium management for the UK EPR involves [Ref-2]:

- Lithium measurements:

The lithium injection process is coupled with the on-line measurement performed in the REN [NSS] and continually transmits in real time to the main control room. The real time determination of the lithium concentration is performed taking into account:

- an electrical total conductivity measurement provided by a sensor;
- the concentration of the impurities in primary water having an impact on the total conductivity value;
- the flow rates approaching the analysers.

Alarms are triggered when the lithium concentration does not meet the chemical specifications and when there is no adapted flow rate. The periodic manual measurements are performed by Atomic Absorption Spectrometry or equivalent laboratory measurement techniques.

- Control of the injection device based on validated algorithms:

The algorithm for the lithium concentration calculation first credits various boric acid dissociations to obtain a reactor coolant system pH value and then uses the conductivity value [Ref-2].

The algorithm for injection starts the dosing pump when the measured deviation from the lithium concentration setpoint is significantly large and stops the pump when the deviation has subsided. The lithium concentration setpoint is reached after the time necessary for complete mixing of the lithium solution in the RCP [RCS].

In case of a large deviation ( $> 0.1$  mg/kg) from the specified lithium concentration, a first alarm is triggered (normally, the I&C would switch off the lithium injection pump when the difference between the measured lithium concentration and the required lithium concentration falls below 0.04 mg/kg). In the case of very large deviation ( $> 0.5$  mg/kg) from the lithium concentration specification, a second alarm is triggered.

- Injection system:

The injection of lithium solution into the reactor coolant system at the high pressure (HP) charging pump inlet is performed via a device including an injection tank and an injection dosing pump [Ref-1].

- Lithium removal:

In case of high lithium concentration, the excess lithium from the reactor coolant is removed by the lithium removal mixed bed demineraliser.

### **1.2.3. Evidence supporting the Application of Zinc Injection of the UK EPR**

#### **1.2.3.1. Identification and Quantification of Evidence**

The zinc injection application in the primary coolant is associated with the following claims [Ref-1] to [Ref-3]:

- Radiation field and dose management due to the replacement of cobalt in the ex-core surfaces by non-radioactive zinc, as well as the reduction in general corrosion leading to a decrease in the source term
- Minimisation of fuel CRUD, due to the minimisation of releases from the SG tubes and the reduction of residence time of corrosion product deposits on the fuel cladding ;
- No deleterious impact on material integrity;
- Minimal impact of zinc injection on waste and discharges;
- Improvement of the operating unit availability due to the preventive nature of minimisation of the effects of CRUD (anticipated shutdowns and/or power reduction caused by AOA/CIPS events and/or corrosion cladding failure, CILC). In addition, the dose rate minimisation contributes to improving the working conditions during maintenance operations.

The evidence justifying the efficient action of zinc injection in the different claims falls into three categories:

- Theoretical evidence:
  - spinel structures demonstrate the capacity of zinc to inhibit or replace the other ionic elements (mainly cobalt);

- thermo dynamical calculations showing the stability of zinc chromite in the inner layer of oxides.
- Evidence from laboratory tests demonstrating for several materials:
  - general corrosion reduction leading to reduction of the source term;
  - minimal impact on material integrity due to the absence of cladding corrosion.
- Evidence from NPP OPEX demonstrating:
  - deposit activity and dose rate reduction;
  - AOA mitigation in plants affected by this phenomenon in previous cycles before application of zinc injection;
  - AOA prevention in plants having applied a change in fuel management.

The potential actions of zinc have been assessed, and an analysis of the evidence associated with the arguments supporting zinc injection [Ref-3], demonstrates the following:

- The argument “Positive effect on dose rates” is supported by a global dose rate reduction of 10 to 15%. This estimation is based on:
  - reduction of the source term by means of general corrosion reduction: reduction is estimated to be about 50% in the presence of zinc;
  - reduction of deposited activity in the primary circuit surfaces due to the Co-60 inhibition and/or replacement by zinc: reduction of Co-60 incorporation is estimated to be about 12%;
  - PWR feedback showing dose rate reductions of 20 to 40% in operating units and 70% for new reactors;
  - the average reduction of diffusion and rate coefficients for stainless steel and Alloy 690 is approximately 10%.
- The argument “Positive effect on fuel integrity and unit availability” is supported by:
  - reduction of the source term by means of general corrosion reduction: reduction is estimated to be about 50% in the presence of zinc;
  - qualitative reductions observed in the reduction of fuel CRUD according to NPP feedback (about 30%) due to the reduction of residence time on the core and uniform distribution preventing AOA and CILC events;
  - absence of a negative effect on cladding corrosion and fuel failures.
- The argument “Positive effect on material integrity” is supported by:
  - reduction of the source term by means of general corrosion reduction: reduction is estimated to be about 50% in the presence of zinc;

- due to the selection of Alloys 690/152/52 for the UK EPR, the second barrier provides good resistance to Primary Water Stress Corrosion Cracking (PWSCC). Therefore, for the UK EPR the potential impact of zinc injection has not been explicitly evaluated as it has been done for other materials. However, no negative effects have been observed from existing plants performing zinc injection and operating with Alloy 690/152/52 materials.
- The argument “minimal impact of zinc injection” is supported by:
  - feedback and laboratory tests demonstrating:
    - no AOA/CILC event attributed to zinc;
    - no CRUD or thickness increase;
    - no impact on the safety analysis of flammable mixtures, reactivity;
    - no negative impact on integrity of RCP [RCS] components and instrumentation;
    - no negative impact on the environment from waste and effluents.

As a global assessment, it is underlined that benefits from zinc injection are expected, without exception, for the UK EPR. Zinc injection efficiency has been considered from the early UK EPR design stages and the final results will ultimately depend on the operating cycle conditions.

#### **1.2.3.2. UK EPR Zinc Injection Implementation**

Zinc injection application for the UK EPR has been considered during the design of the UK EPR. The necessary actions and measurements have been established in order to take maximum account of the benefits of this practice whilst considering input from risk analysis and human factors considerations.

The zinc injection process for implementation on the UK EPR incorporates:

- Selection of additive;
- Specific Zinc Injection System;
- Specific Zinc Injection Monitoring;
- Specific operating procedures and specifications.

##### **1.2.3.2.1. Selection of Additive**

Zinc will be injected as depleted zinc acetate ( $C_4H_6O_4Zn \cdot 2H_2O$ ) with specific characteristics [Ref-1] [Ref-2].

The selection of depleted zinc instead of natural zinc is justified by:

- Zn-65 limitation in the oxide layers of primary circuit surfaces in order to optimise the dosimetry benefit;

- Zn-65 limitation in effluents and waste.

The selection of zinc acetate is justified by:

- The high solubility of acetate when compared with other possible additives (borates, formates) which limits precipitation into the injection lines and allows easier staff chemistry activities concerning the maintenance of the injection system device.
- International experience showing the absence of negative impacts on:
  - carbon production;
  - waste production;
  - filter and resins consumption;
  - CRUD deposition on fuel cladding.

#### **1.2.3.2.2. Zinc Injection System [Ref-1]**

The zinc injection system is a specific injection system included in the RCV [CVCS] in order to facilitate human operations and to improve the zinc injection effectiveness and monitoring. The following components have been integrated into the design:

- Dedicated lines: The injection of zinc acetate is separated from other reagents thanks to a dedicated line. In this way, the mixing of zinc with other elements is avoided.
- Alarm and sensor integration: Human intervention is limited due to parameter monitoring by sensors and associated alarms.
- Protection implementation:
  - in case of a low level in the zinc injection tank;
  - during injection of lithium in order to avoid the risk of precipitation due to the potential increase of pH solution as a consequence of Li and Zn mixture.
- Flushing line implementation: The potential for human intervention is reduced due to the integration of flushing lines providing demineralised water from the SED system to the zinc injection tank.

The REN [NSS] design takes into account the increased knowledge and experience of sampling of corrosion products with regard to fluctuations due to the sampling locations (RCP [RCS] hot leg and RCV [CVCS] letdown), and the delay in detection. For optimisation of zinc injection monitoring, the REN [NSS] of the UK EPR has been designed taking into consideration:

- International and AREVA/EDF feedback;
- International guidelines.

The zinc injection monitoring of the UK EPR is further enhanced by:

- The integration of RCV [CVCS] sampling allowing:
  - earlier detection of the presence of zinc in the primary coolant;
  - minimisation of the zinc concentration fluctuations.
- The grab sampling analyses performed in the nuclear auxiliary building laboratory of corrosion products [Ref-2];
- The analysis of soluble and insoluble activity from the RCV [CVCS] and Fuel Pool Cooling System (PTR [FPCS]);

Based on what has been stated above, the following can be claimed:

- Zinc injection of the UK EPR will be performed meeting all the requirements concerning installation and human risks;
- Zinc injection will be correctly monitored in order to meet the chemical and radiochemical specifications, and with the objective of collecting the necessary data to evaluate the effects of zinc allowing the application of progress and optimisation.

The necessary documentation and operating procedures to ensure the optimal application and to facilitate the necessary staff actions are outlined below:

- Preliminary chemical specifications [Ref-1] [Ref-3]:

Parameter	Preliminary EPR Specifications	Justifications
<b>[Zn]</b>	Expected range: $5 \mu\text{g/kg} < [\text{Zn}]_{\text{measured}} < 15\mu\text{g/kg}$ with a target concentration of $10\mu\text{g/kg}$	Main goal is for radiation field benefits obtained for this range
	Limit Value : $[\text{Zn}]_{\text{max}}=40 \mu\text{g/kg}$	Conservative value to prevent CRUD deposition
<b>[Ni] total</b>	3 $\mu\text{g/kg}$	Value to prevent the CRUD deposition
<b>[SiO<sub>2</sub>]</b>	1.0 mg/kg	Values to prevent zeolites deposition
(*) Also applied for units without zinc injection		

- Risk analysis and operating procedures: The frequency of measurement and the associated actions are dependent on the injection phase. These phases have been established taking into account the feedback to determine of the operating zones (zinc Implementation).

**1.2.4. Evidence supporting the UK EPR Hydrogen Programme**

Hydrogen addition into the primary coolant during power operation is justified by the requirement to scavenge oxygen and the radiolysis produced oxidant. It is necessary to ensure that oxidising conditions do not develop in the reactor core or elsewhere in the reactor coolant system.



Hydrogen management is associated with the following claims:

- Material integrity: due to possible material corrosion of the primary circuit in the presence of oxygen.
- Safety: due to hydrogen degassing in vessels leading to the potential H<sub>2</sub>/O<sub>2</sub> mixture.
- Radiation field management: due to the influence of hydrogen on the redox potential of the medium and consequently on the corrosion product solubility.
- Plant Operational Availability: due to a requirement to optimise the hydrogen elimination during shutdown in order to meet the requirements necessary to proceed to forced oxygenation of the primary coolant (to avoid H<sub>2</sub>/O<sub>2</sub> risks)

Depending on the reactor state, the amount of hydrogen injected and the procedures applied to maintain or eliminate the hydrogen present in the primary coolant are a compromise between the different risks and benefits identified. The important issues that need to be determined in normal operation and during shutdown are listed in the table below.

Domain	Material Integrity	Safety	Activity Management
Main Issues	Oxygen ingress effect on material	System design (TEG [GWPS]) to ensure the minimum flow rates in the vessels to ensure H <sub>2</sub> gas < 4% and O <sub>2</sub> gas < 2%	Optimal hydrogen concentration to minimise: <ul style="list-style-type: none"> <li>• the corrosion product transfer between the ex-core surface and the fuel assemblies,</li> <li>• the corrosion product precipitation in the core (CRUD)</li> </ul>
	The minimum hydrogen level to suppress radiolysis in the water phase in the core	The degassing systems and associated procedures to ensure a rapid hydrogen elimination before primary circuit head-lift	
	The sub-cooled nucleate boiling on fuel assemblies in the core deplete the hydrogen in the water phase below this minimum hydrogen concentration		
	Hydrogen pick-up by fuel cladding		
	The maximum value to prevent hydriding cladding		
Secondary Issue	The optimal concentration to reduce the SCC growth risk		

### 1.2.4.1. Identification and Quantification of Evidence

#### 1.2.4.1.1. Material Integrity

A minimum concentration of hydrogen in the primary coolant has to be ensured in order to prevent water radiolysis and hence production of the oxidant products ( $O_2$  and  $H_2O_2$ ) and the radicals (reactive species) e-aq,  $H^+$  and  $OH^-$ . Each of the oxidants and radicals lead to several possible reactions with  $O_2$ .

The presence of  $H_2$  prevents water radiolysis decomposition. Evidence is available to select the minimum hydrogen concentration at  $300^\circ C$  required to prevent water radiolysis decomposition [Ref-1].

Modelling studies: According to these studies the minimal hydrogen concentration required is between  $0.3$  and  $1 \text{ cm}^3$  (STP)/kg [Ref-1].

In the case of core boiling, it is possible to observe hydrogen depletion in the liquid phase due to hydrogen transfer to gas bubble. Calculations have shown that a void fraction of 10% leads to 20% hydrogen depletion in the liquid phase. Thus, even at this high void level 80% of the dissolved hydrogen remains in the liquid phase [Ref-1].

NPP experience: Values between  $1.3$  and  $5 \text{ cm}^3$  (STP)/kg have been measured.

Laboratory tests: M5® worldwide experience demonstrates very good corrosion resistance of this material even in high duty plants with nucleate boiling up to 8% ensuring that about 85% of the dissolved hydrogen remains in the liquid phase which is still largely sufficient to suppress radiolysis.

Based on these elements the minimal necessary value of dissolved hydrogen to ensure radiolysis suppression is:

- $5 \text{ cm}^3$  (STP)/kg without considering eventual local boiling;
- $10 \text{ cm}^3$  (STP)/kg considering an envelope of boiling risks with a void fraction of 25%, much higher than that estimated for UK EPR.

The high level of hydrogen is limited by the hydriding cladding process that occurs when the hydrogen solubility becomes higher than that of zirconium and the hydrogen is picked up in the cladding. This phenomenon can induce fuel failure degradation. No data on the effects of hydrogen concentrations higher than  $50 \text{ cm}^3$  (STP)/kg on Zr-based alloys are available in the public domain [Ref-2]. Therefore the high limit value has been fixed at  $50 \text{ cm}^3$  (STP)/kg.

Taking into account the choice of the UK EPR RCP [RCS] primary component materials: stainless steel, and Alloy 690TT (the main material surface in contact with the coolant) and the high PWSCC resistance of this latter alloy compared to Alloy 600 [Ref-1], the definition of a minimal hydrogen concentration of  $10 \text{ cm}^3$  (STP)/kg and a maximal concentration of  $50 \text{ cm}^3$  (STP)/kg is acceptable regarding the RCP [RCS] material SCC risks during normal power operation.

During shutdown the risk of Low Temperature Crack Propagation (LTCP) on nickel-based alloys is minimised by limiting the hydrogen concentration in the primary coolant at temperature lower than  $150^\circ C$  [Ref-1].

**1.2.4.1.2. Safety**

The absence of risk is defined by verification that the hydrogen and oxygen concentration is lower than flammability limits:

If  $H_2 > 4\%$  and  $O_2 > 4.8\%$  --> flammability risk

Therefore, in order to avoid the hazardous gas mixtures, it is necessary to ensure  $H_2$  and/or  $O_2$  values are lower than flammability limits in the vessels and lines where a flammable mixture can be accumulated [Ref-1].

Prevention of the formation of flammable mixtures of oxygen and hydrogen, in the components of the reactor coolant system and auxiliary systems where gases can accumulate, is ensured for the UK EPR during every phase of operation due to design considerations and operating and chemistry procedures [Ref-2].

- During power operation (state A):
  - hydrogen and oxygen in the gas phase within components and systems (VCT, RPE [NVDS], pressuriser to RPE [NVDS], TEP [CSTS]) are constantly swept by  $N_2$  flow from the TEG [GWPS] ensuring  $H_2 < 4\%$  and  $O_2 < 2\%$ ;
  - the TEG [GWPS] uses a recombiner downstream of the system components, where gases can accumulate, to ensure elimination of residual  $H_2$  and  $O_2$  concentration ( $O_2 < 0.2\%$  and  $H_2 < 0.3\%$ ).
- The online monitoring, and the subsequent data transmission to the control room, of hydrogen and oxygen in the primary coolant by the REN [NSS] ensures the immediate identification of possible deviations from the target values. Periodic manual controls are performed by chemistry staff.
- During shutdown (states B to F):
  - the hydrogen concentration is reduced before shutdown;
  - the hydrogen and oxygen concentration in the gas phase of system components is continually removed by TEG [GWPS], TEP4 [CDS] and pressuriser degassing;
  - the  $H_2$  injection stops before 1<sup>st</sup> train of RIS/RRA [SIS/RHRS] connection;
  - the RIS/RRA [SIS/RHRS] connection leads to  $O_2$  ingress but  $O_2$  removal is ensured by hydrazine injection and the continual degassing of the primary circuit and connected system components;
  - before the oxygenation phase, the  $H_2$  concentration is completely removed ( $H_2 < CH_2$  fixed by chemistry specifications); if higher concentrations are measured, chemical dehydrogenation can be applied in order to eliminate the residual  $H_2$  by injection of  $H_2O_2$ .
- During start-up:
  - in order to prevent  $H_2/O_2$  mixtures, hydrogen must be added into the primary coolant only if the removal of oxygen has been completed: the  $H_2$  concentration is added just before reaching criticality;

- in order to prevent corrosion risk of the primary material, O<sub>2</sub> concentration is < 0.1 mg/kg when T > 120°C.

#### 1.2.4.1.3. Radiation Field / CRUD Management

Selection of the hydrogen concentration required with respect to radiation field and CRUD management is established according to the same principles given for the pH management programme outlined in section 1.2.2:

- Minimise the corrosion product transfer to the core:
  - reduction of general corrosion and release corrosion rates of primary circuit surfaces;
  - reduction of corrosion product solubility in the core inlet surfaces (low temperature around 290°C).
- Minimise the corrosion product deposition in the core:
  - reduction of the source term likely to be deposited in the core (mainly the species found in the upper regions of the assemblies where the deposition risk is higher due to the greater boiling rates);
  - increase corrosion product solubility in the core outlet surfaces (high temperature around 320°C).

However, evidence is based on different phenomena than those used in the selection of an optimal pH programme. It should be recognised that there are many parameters that have an influence on activity transport and deposition. The effect of hydrogen is not yet completely understood due to determination of the redox potential (function of hydrogen and oxygen concentrations) and the consequent effect on thermodynamic stable phases. In spite of the difficulties, some trends are observed from:

#### NPP experience:

PWR testing hydrogen concentration modifications [Ref-1] have shown beneficial impacts on out-of-core deposit activity, dose rates and CRUD deposition following hydrogen concentration reduction.

#### Calculations:

Detailed thermodynamic calculations have been performed to understand the benefits of hydrogen. In the literature, there are interpretation discrepancies due to the concurrent influence of several factors.

The table below shows that:

- At a low temperature (core inlet) the stable nickel form is Ni or NiO for hydrogen concentrations higher or lower than 10 - 17 cm<sup>3</sup> (STP)/kg, respectively;
- At elevated temperatures (core outlet) the stable nickel form is Ni or NiO for hydrogen concentrations higher or lower than 30 - 53 cm<sup>3</sup> (STP)/kg, respectively.

	Stable form	H <sub>2</sub> concentration
Assembly bottom (core inlet) 285°C	NiO	< 10 - 17 cm <sup>3</sup> (STP)/kg
	Ni	> 10 - 17 cm <sup>3</sup> (STP)/kg
Assembly top (core outlet) 335°C	NiO	< 30 - 53 cm <sup>3</sup> (STP)/kg H <sub>2</sub>
	Ni	> 30 - 53 cm <sup>3</sup> (STP)/kg H <sub>2</sub>

The discrepancies in the thermodynamic results can be explained by the change in the stable form and the simultaneous temperature influence. Furthermore, it should be noted that the hydrogen effect on corrosion product management, based on thermodynamic results, is interpreted in different ways depending on the approach followed:

- Assuming that the most beneficial scenario corresponds to the conditions enabling the thermodynamic stability of the species with higher solubility in the core outlet temperature and lower solubility in the core inlet temperatures.
  - For the core inlet surface, the iron and nickel species with lower solubility are preferred in order to limit the source term release from the ex-core surfaces. Therefore, minimisation of iron and nickel species solubility constitutes the first step of limiting the transfer of corrosion products.
  - For the upper regions of the rods, the CRUD is rich in nickel coming from Ni and NiO. Since Co-58 is produced by nickel activation, limitation of nickel deposition in the core is the second step in minimising the activation of corrosion products.
- Following the above principles the hydrogen concentration range is selected to achieve the optimal conditions of iron and nickel solubility depending on the temperature:
  - For the core inlet, the goal is minimisation of the iron and nickel solubility:
    - The total iron solubility (mainly from ferrites) decreases with hydrogen decrease. Therefore, a low hydrogen concentration is considered beneficial for low ferrite solubility and to minimise the ferrite transfer to the core.
    - The Ni presents lower solubility than NiO. Therefore, the Ni formation can be enabled with hydrogen conditions higher than 10 – 17 cm<sup>3</sup> (STP)/kg [Ref-1].

With respect to the core inlet, a hydrogen concentration slightly higher than 10 - 17 cm<sup>3</sup> (STP)/kg will minimise the corrosion product transfer from surfaces.

- For the core outlet, the goal is to increase nickel solubility. The total nickel solubility is higher at low hydrogen concentration due to NiO stability. Therefore, a hydrogen concentration lower than 30 cm<sup>3</sup> (STP)/kg is considered beneficial for high nickel solubility and to minimise nickel deposition on the core.

Taking into account the above elements the optimal hydrogen target concentration defined for UK EPR is:

$$17 < H_2 \text{ concentration} < 30 \text{ cm}^3 \text{ (STP)/kg}$$

To ensure the presence of the species with optimal solubility, the H<sub>2</sub> concentration has been fixed for the UK EPR (first approach).

**1.2.4.2. Hydrogen Programme Implementation for the UK EPR**

**1.2.4.2.1. Hydrogen Specifications**

Taking into account all the considerations discussed, the values selected for the UK EPR are as follows:

Values	H <sub>2</sub> concentration (cm <sup>3</sup> (STP)/kg)	Justification
Minimum value	17	Compromise between the minimal concentrations required to suppress radiolysis and the optimal concentration to avoid the core deposition and the corrosion transport.
Maximum value	50	Lack of data concerning fuel cladding hydriding for higher concentrations

**1.2.4.2.2. Hydrogen Injection**

H<sub>2</sub> conditioning in the reactor coolant is carried out by the hydrogenation station [Ref-1] installed in the low-pressure part of the RCV [CVCS].

A minimum of approximately 90% of the letdown flow passes through the hydrogenation station. The remaining flow (< 10%) is routed through the Volume Control Tank (VCT). The hydrogenation station enables a nitrogen blanket to be applied in the VCT during all operating modes (power operation and outage). This nitrogen blanket is flushed by the TEG [GWPS] so that no hydrogen concentration higher than 4% can occur in the gas phase of the VCT.

The main components of the hydrogenation station are: a water jet pump, a gas separator, and a mixing pump. The different components have connections to the gaseous waste processing system, the vent and drain system, and the nitrogen supply system for venting and flushing of the main components.

The hydrogenation station is a self controlling device that automatically injects hydrogen when the concentration in the reactor coolant falls below the target concentration. The target concentration is determined by the pressure in the VCT. The hydrogen concentration at the outlet of the hydrogenation station can be approximately calculated by means of Henry's law of solubility in combination with Dalton's Law.

The control of the hydrogen concentration within the range 17 cm<sup>3</sup> (STP)/kg to 50 cm<sup>3</sup> (STP)/kg is made possible by adjusting the pressure in the VCT.

Start-up and shutdown of the hydrogenation station is performed from the main control room by switching the automatic gas separator level control on or off, and opening or closing the isolation valve on the hydrogen supply line. During start-up, the level in the gas separator falls automatically to its normal level. Occasionally the propellant pressure upstream of the water jet pump can be checked and adjusted for the correct operation of the pump (approximately 12 bar). One pressure sensor with local annunciation and a manual adjusting valve would be at this location.

#### **1.2.4.2.3. Hydrogen Monitoring**

Hydrogen concentration is monitored online by the REN [NSS] and the results are transmitted in real time to the control room. The gas phases of system components are controlled periodically by Gas Chromatography.

Hydrogen monitoring measurements are installed in the rooms related to the hydrogenation station. If hydrogen is detected in the air, an automatic I&C interlock closes the control valve and the isolation valve on the hydrogen supply line in order to stop feeding a possible leak in the gas separator or at the water jet pump. These valves are power supplied by separate electrical divisions. An alarm is activated simultaneously in the main control room.

#### **1.2.4.2.4. Prevention of Internal Hazard in Case of Hydrogen Release**

The hydrogen concentration in the rooms related to the hydrogenation station is monitored by means of KRH sensors. When a leak is detected, the hydrogen supply line to the gas separator is automatically isolated. This is performed by closing two valves installed in series.

Simultaneously, an alarm on the MCP [PICS] and an alarm on the MCS [SICS] are generated. In the case of an isolated hydrogen supply line, if the components integrity is maintained, the operation of RCV [CVCS] is possible since the HP charging pump suction is not affected.

In this configuration only the hydrogenation function is not available.

### **1.2.5. Evidence supporting Activity Management**

Activity management is based on the methodology established for the UK EPR [Ref-1], which includes four fundamental steps:

- Identification of radionuclides;
- Activity quantification;
- Activity characterisation;
- System treatments (section 1.2.2).

In order to address the chemical and radiochemical uses, it is necessary to ensure that the radionuclides selected as indicators support the following claims:

- **Safety management:** The chemical and radiochemical indicators associated with the safety claim are those which need to be monitored during normal operation to comply with the safety demonstration.

- **First barrier integrity:** The routine monitoring of these parameters identifies the occurrence of fuel failures and tracks their progression and characterisation.
- **Material integrity of primary circuit (excluding fuel cladding):** monitoring of these parameters will enable detection of possible material degradation and/or pollution with potential impact on the radiation fields, dose rates, or surface contamination.
- **Environment:** The indicator selected should allow control of the long-lived isotope production that will show up in radioactive waste.
- **Radiation field:** The indicators associated with this claim are those which enable the following:
  - detection of possible changes in primary coolant activity and its consequences on dose;
  - identification of abnormal operating conditions that have an influence on radiation fields; these are filters and demineraliser performance with the objective of avoiding radionuclide releases and/or accumulation in the circuits and minimising human intervention with the associated exposure risk.
- **Operational Availability:** monitoring of indicators associated with this claim will help to identify reactor coolant events with a possible impact on operating conditions during full power, transient periods, and shutdown such as CRUD burst, forced or refuelling shutdowns, development of AOA, etc.

The correct selection of these isotopes is necessary in order to provide accurate information on the state of the unit during the different phases of operation. Furthermore, these indicators are the input information for consideration in the design, sizing, and equipment of the sampling system (REN [NSS]) and analysis laboratory.

#### 1.2.5.1. Indicators Associated with Safety Management

In practice, these indicators concern the parameters of one or more values if they are exceeded during normal operation, the criteria defining the transients, incidents or accidents are breached [Ref-1] [Ref-2].

These indicators are classified in three categories:

- Indicators considered as initial conditions for the radiological consequence studies.
- Indicators that ensure the availability of the required mitigation system.
- Indicators that ensure the monitoring of the containment barrier integrity during the short term.



Category of Associated Indicators	Parameter Selected	Comments
Initial condition for the radiological consequences studies	Eq. I-131(max) (*) Applied in operation and transient periods (state A-B)	Activity used as reference to estimate the radiological consequences of accidents during power operation and transient periods.
	$\sum \text{Gasmax} =$ Xe-133 + Xe-133m + Xe-135 + Xe-138 + Kr-85m + Kr-87+Kr-88 Applied in operation (state A)	The maximum value of the $\sum \text{Gas}$ activity governing the execution of a power transient to verify that the peak iodine activity is less than the limiting Eq. I-131 activity value under transient operating conditions.
	Eq. I-131(max) Applied during outages (states C, D, E) with RIS/RA [SIS/RHRS] in service	Activity used as reference to estimate the radiological consequences of break incidents/ accidents during an outage inside the Reactor Building assuming that the third barrier is open.
Availability of a mitigation procedure	Volatile Iodine limitation Applied to states A, B, C, and D.	The NaOH is required to achieve alkaline conditions in the IRWST in order to limit the volatile iodine in the containment during LOCA or severe accident.
	Minimum NaOH concentration in the EVU [CHRS]	Specification to achieve the minimum pH to prevent volatile iodine formation.
	Maximum NaOH concentration in the EVU [CHRS]	Specification to prevent the crystallisation in the tanks.
Control of the containment barriers integrity in short term (fuel integrity monitoring).	Xe-133 Xe-133/Xe-135	Selection of fission products in RCP [RCS] with the necessary characteristic to identify the presence of a cladding defect.
	Xe-133 activity in RCP [RCS] Applied in operation (state A)	Specification of minimal Xe-133 activity permitting the distinction of fuel failure.
	Xe-133/Xe-135 Applied in operation (state A)	Minimal ratio for the identification of fuel cladding failure.

$$(*)\text{EqI131}(MBq/t) = I131 + \frac{I132}{A} + \frac{I133}{B} + \frac{I134}{C} + \frac{I135}{D}$$

As indicated, the table below provides the values of coefficients used in EDF guidelines for French NPPs [Ref-2] and other international guidelines.

Isotope	EDF Factor	(USNRC, 1963)	(USNRC, 1977)	(ICRP-30, 1980)
(I-131)	1	1	1	1
A(I-132)	30	27.70	104.16	170.65
B(I-133)	4	3.70	5.52	5.92
C(I-134)	50	59.17	400	1000
D(I-135)	10	11.93	26.59	34.13

**1.2.5.2. First Barrier Integrity Monitoring**

The activity measured in the primary coolant samples taken by the Nuclear Sampling System (REN [NSS]) is the main data input for fuel failure detection and its characterisation. The radionuclides released through cladding defects are the **fission products**. The accuracy of modelling and empirical assessments performed during a cycle depends greatly on the nuclides used as indicators [Ref-1] [Ref-2]. Noble gases and iodine isotopes are considered as suitable candidates for radiochemical evaluation concerning the fuel cladding integrity as they meet the following required criteria:

- Isotopes produced by the fission reactions for which release from the gap cladding into the primary coolant is greater due to their high cumulative fission yields;
- Isotopes with appropriate half lives:
  - long enough in order to ensure their transfer through the gap cladding and their subsequent detection by routine method of analysis compatible with the regular chemistry activities;
  - short enough to ensure representative activities (by comparing with the number of atoms  $(A_i = \lambda_i N)$  released into the primary coolant) following a fuel failure onset and/or defect degradation.
- Isotopes easily identified in the primary coolant by a common measurement technique with counting and analysis times compatible with the frequencies requested by Radiochemistry Specifications. This technique should not require complex devices in order to ensure the complete control by chemistry staff of the plant laboratory. At present, the gamma spectrometry is the most adapted technique to identify the radionuclides in PWR circuits. The selected isotopes should have distinct gamma rays energies in order to prevent the possible interference with other nuclides.

Based on the above criteria, the selection of fission products used to monitor the fuel cladding state during reactor operation is listed in the table below.

Isotope	Cumulative Fission Yield (%)	T <sub>1/2</sub>	Gamma Ray 1 keV (%) (a)	Gamma Ray 2 keV (%) (b)	Gamma Ray 3 keV (%) (b)
Kr-85m	0.93	4.48 h	151.2 (75.1)	304.9 (13.7)	
Kr-87	1.76	1.37 h	402.6 (49.6)		
Kr-88	2.44	2.84 h	196.3 (26.0)	834.8 (13.0)	1530 (10.9)
Xe-133	6.84	5.24 d	81.0 (38.3)		
Xe-135	7.07	9.10 h	249.8 (90.2)		
Xe-138	5.77	14.10 m	258.3 (31.5)	434.5 (20.3)	1768.3 (16.7)
I-131	3.37	8.04 d	364.5 (81.2)		
I-132	4.86	2.28 h	667.7 (98.7)	772.6 (76.2)	
I-133	6.81	20.8 h	529.9 (86.3)		
I-134	7.49	52.6 m	847.0 (95.4)	884.1 (65.3)	
I-135	6.38	6.57 h	1260.4 (28.9)	1131.5 (22.5)	

References:

- (a): (Nichols, et al., Handbook of Nuclear data / IAEA-INDC(NDS)-0502-2007);  
(Nichols, et al., Handbook of Nuclear data, IAEA-INDC(NDS)-0534-2008)
- (b): (Kocher, Radioactivity Decay Data Tables, DOE/TIC-1981)

**Nuclides Used in Fuel Performance Evaluations:  
Decay Characteristics, Gamma Ray and Intensities**

It should be noted that caesium isotopes are not used for fuel failure detection but for estimation of burn-up. As explained in the following paragraph, the caesium release is mainly detected during the power transient periods and can be used to estimate the rod burn-up. Not all fission products provide the same type of information concerning the fuel cladding defect. An overall assessment is needed in order to link the individual pieces of information provided by the activity trends of each nuclide to provide an accurate diagnosis.

The diagnosis process includes three evaluations:

- Fuel failure detection based on Xe-133 trend activity and the Xe-133/Xe-135 ratio;
- Tramp uranium evaluation based on I-134 activity trend;
- Fuel failure characterisation based on the determination of burn-up (by the monitoring of Cs-134/Cs-137), the nature of a fuel leaking rod UO<sub>2</sub>-MOX (by the monitoring of Kr-85m/Xe-135), and the linear power of fuel leaking rods (by activity trends and spike during transients).

**1.2.5.2.1. Fuel Failure Detection**

The first step in fuel evaluation is to determine the existence of fuel failures. During a cycle, the onset of fuel failure can be easily detected by noble gas surveillance rather than iodine activity. Activity variation is easier to identify in gas isotopes because iodine has the tendency to be trapped in the gap cladding due to its chemical characteristics i.e. absorption on the internal cladding surface.

In contrast, noble gases are inert chemical species whose release from the fuel-to-cladding gap is not affected by absorption phenomenon and they expand further filling up the plenum region. Fission gases escape more readily from fuel defects than iodine and consequently the cladding leaks can be detected earlier by gas fission changes even if iodine activity remains stable.

In particular, the trend in Xe-133 activity is normally used as an indicator of fuel integrity in view of the fact that it is the isotope that complies best with the required criteria. It belongs to the category of fission products with high fission yields and its half-life is long enough to ensure its transport from the gap to the primary coolant. At the same time, it can be detected by gamma spectrometry because its half-life is short enough to reach equilibrium in a few days with a representative activity and its single ray at 81 keV cannot be masked by that of other significant nuclides in primary coolant.

Feedback analysis shows that it is not possible to generalise the activity released by a defect because it greatly depends on the type of defect (rod power, localisation, burn-up, size, etc.) and in addition, the Xe-133 activity may be significantly influenced by the presence of tramp uranium in the core. For this reason, fuel failure identification is based on the following isotopic ratio monitoring:

- The principle of fuel cladding evaluation consists of comparison of the short and long lived isotope activities using isotopic ratios. Following defect onset, the longer half-life noble gas isotopes become dominant compared to the shorter ones: Xe-133 > Xe-135 > Xe-138.
- Xe-133/Xe-135 ratio is used preferentially as an indicator of cladding defects. A value of this ratio higher than 0.9 is observed in the presence of defects. Other noble gas ratios (Xe-133/Kr-87 and Kr-85m /Kr-87) are suggested in the literature to verify the presence of defects but they are less consistent to distinguish the presence of a fuel failure.
- Evaluation of the activity attributed to the tramp uranium helps to distinguish the presence of micro defects and anticipate the alpha risk.

Based on the comments above, and in compliance with international guidelines [Ref-1] [Ref-2]:

- The Xe-133/Xe-135 ratio is used as the main indicator of fuel cladding defect detection independently of the Xe-133 activity; and/or
- A maximal Xe-133 activity value for identifying a cladding defect.

#### **1.2.5.2.2. Tramp Uranium Evaluation: alpha risk assessment**

Tramp uranium is the fissile material present in the primary coolant from two sources:

- Manufacturing processes leading to contamination of the fuel pellets on the cladding rods;
- Disseminated defects leading to the release of fissile material through the leaks.

Isotope candidates selected as tramp uranium tracers should be characterised by properties providing firstly an alert for uranium debris presence in the primary coolant and secondly to allow the activity associated with this source to be quantified. For that, the indicator should verify the following characteristics:

- To be a relevant isotope whose presence in the primary coolant could be attributed “almost” exclusively to the mass uranium in direct contact with the water of primary coolant, i.e., the activity directly released by the defects is neglected comparing with the activity released by the fissile material.
- The marker isotope can be:
  - An isotope from a radionuclide with low mobility in the fuel matrix such as Rubidium, Strontium, Zirconium, Actinides, Lanthanides. The detection of these elements in the primary coolant should be considered as an indication of a severe fissile material dissemination.
  - A short half-life fission product isotope whose activity can be mostly attributed to the tramp uranium, even in presence of leaking rods. Due to their short radioactive period, the short-lived isotopes mainly decrease in the gap before reaching the cladding defect.
- To be measurable in the primary coolant during normal power operation in order to detect as soon as possible the presence of fissile material. Based on this second criterion, the fission products with short half-life, routinely and directly measured in the primary coolant by gamma spectrometry, are the most pertinent tracers to monitor the tramp uranium contamination in the primary coolant.

From these indications, the most suitable candidate currently identified for the recurrent monitoring of the tramp uranium activity in primary coolant is I-134. It can be clearly identified using gamma spectrometry, and its half-life is long enough to allow detection in the primary coolant and at the same time sufficiently short to be representative of the recoil process from the tramp activity. Nevertheless, feedback reveals that I-134 activity can fluctuate. Complete understanding of these fluctuations requires further analysis correlating the fission product activity with the sampling conditions, the operation conditions, and the concentration of other nuclides present in the primary coolant. The UK EPR laboratory and the REN [NSS] are equipped to carry out complementary analysis of alpha spectrometry and global alpha activity.

### **1.2.5.2.3. Fuel Failure Characterisation**

Monitoring and activity analysis of specific fission products during steady operation and shutdown constitute the basis for the discrimination of leaking rods and their characterisation:

- Burn-up determination of leaking rods is based on Cs-134/Cs-137 measured during shutdown. This ratio depends on fuel nature and enrichment.
- Nature of fuel cladding defect is determined by the measure of Xe-135/Kr-85m in steady conditions. This ratio is analysed in units with mixed cores (MOX and UO<sub>2</sub> assemblies).
- The linear power of leaking rods is the most difficult characteristic to estimate because it is influenced by the assembly localisation in the core, the rod placement inside the assembly, and the defect presence in the upper or lower regions of rods. The parallel analysis of the activity profile trends of <sup>133</sup>Xe and <sup>131</sup>I during the cycles and transient periods can provide indications concerning the linear power of leaking rods.

Defect numbers cannot be easily quantified. These depend on defect characteristics and a diagnosis can be provided by coupling the qualitative analysis of the activity in the primary coolant with the simulations performed with diffusion and/or kinetic models of fission product release [Ref-1].

**1.2.5.3. Material Degradation Monitoring**

Generally, the dominant corrosion product radionuclides are formed from the most abundant transition metals (iron, nickel, and chromium) in the RCP [RCS] structural alloys, and cobalt from Stellites. Under some circumstances, other elemental species such as antimony and silver can be equally important. In addition to the measures taken to reduce the content of these elements in the UK EPR [Ref-1], the monitoring of activated nuclides is used to detect any possible anomalies.

The table below lists the main isotopes whose activity increase can be associated with specific component degradation.

Nuclide	Origin	Reaction	Half-life
Co-58	Nickel base alloys (Alloy 690) and Stainless steels	Ni-58 (n,p)→ Co-58 [β+] Co-59 (n,2n)→ Co-58 [β+] Mn-55 (α, n)→ Co-58 [β+]	71 d
Co-60	Impurities of other metallic materials Stellite™, (MCP, RPV internals, CRDM)	Co-59 (n, γ)→Co-60 [β-] Ni58→Co-58→Co-59→Co-60	5.3 y
Mn-54	All the metallic materials	Fe-54 (n, p)→ Mn-54 [K]	312 d
Fe-59	All the metallic materials	Fe-58 (n, γ)→Fe-59 [β-]	45d
Ag-110m	Neutron-absorbing Alloy Ag-In-Cd contained in control rods  Some silver coated seals	Ag-109 (n, γ)→Ag-110m	250 d
Sb-124	Secondary neutron source	Sb-123 (n, γ)→Sb-124 [β-]	60 d
Sb-122		Sb-121 (n,γ)→ Sb-122 [β]	2.7 d
Sb-125		Sn-124 (n, γ)→Sn-125 [β-]→Sb-125 [β-] Sb-123 (n, γ)→Sb-124 (n, γ)→Sb-125	2.8 y
Cr-51	Activation of corrosion products released by Stainless Steels and Nickel base Alloys	Cr-50 (n, γ) →Cr-51 [K]	28 d

**Main isotopes coming from the materials**

N-16 is a useful nuclide for monitoring primary to secondary leaks when plant radiation monitors are installed for that purpose. The SGTR (Steam Generator Tube Rupture) prevention for the UK EPR is based on the N-16 measurement in the main steam line of the secondary circuit with the installation of N-16 detectors.

#### 1.2.5.4. Traceable Radionuclide Activity in Discharges

The isotopes with an important impact on effluents are those with long half-lives,; Fe-55, Ag-108, Nb-94, C-14, Ni-63, Sr-90, Sr-89, **Kr-85**, **Xe-133**, Xe-131m, H-3, Pu-238+239+240+241, Am-241, Cm-243+244.

Among these radionuclides, it should be noted that the fission products Sr-90, Sr-89, **Kr-85**, **Xe-133**, Xe-131m, H-3 do not verify the criteria for assessing fuel failure indicators (due to their long half-life, low fission yield or no gamma emission). However, they can show representative activities in the UK EPR waste systems or in specific conditions during the cycles:

- Kr-85 is a long lived isotope (half-life 10.73 years) with a gamma ray at 514 keV of very low intensity (0.44%) whose detection in the PWR primary coolant during the fuel cycle is masked by the activities of closed nuclides in the gamma spectrum with lower half lives and higher intensities. For instance Co-58 with a half-life of 70.88 days and a second gamma ray at 511 keV (30%) can mask the Kr-85 activity.

After decay of the main nuclides of the primary coolant, Kr-85 can be detected; Kr-85 can present representative activities in the Gaseous Waste Processing System (TEG [GWPS]) due to its accumulation and becomes the dominant fission product in the gaseous discharges after the delay beds.

- Xe-131m is an isotope with an appropriate half-life (11.9 days) for measurement in the primary coolant but its cumulative fission yield ( $3.7 \times 10^{-2}\%$ ) and intensity ( $I=2\%$ ) of its gamma emission ( $E=164$  keV) are not significant. However, Xe-131m activity coming from I-131 can reach representative activities in waste volumes after accumulation of sufficient iodine.
- Sr-90, Sr-89 are beta pure emitters which cannot be monitored routinely. Nevertheless under primary coolant conditions, ( $pH_{300^{\circ}C}$  of 6.9 to 7.4) studies regarding strontium behaviour indicates that strontium is mainly adsorbed onto hydrous ferric oxide surfaces and its soluble activity is not very significant. The special measurement programmes which have been established at existing NPPs have confirmed the strontium activity during steady operation and the ability to detect it during shutdown following pH and temperature decreases.
- C-14 is a radioisotope with a long half-life (5,730 years). It is a low-energy pure beta emitter ( $E_{max}=156$  keV) which is produced in the primary coolant of a PWR mainly from the following reactions:

The main contributors identified are the following:

- O-17 ( $n,\alpha$ ) C-14: O-17 comes from the water of the primary coolant
- N-14( $n,p$ ) C-14: N-14 comes from the tank atmosphere and the hydrazine

The other contributors (minor contribution) identified are:

- C-12 ( $n,\gamma$ ) C-13 ( $n,\gamma$ ) C-14

- C-13 (n,γ) C-14
- The main sources are neutron activation of O-17 which is an isotope of oxygen contained in the water coolant and N-14 (depending on the concentration of dissolved nitrogen in the primary coolant). C-14 production from carbon activation is very low compared to that formed by oxygen and nitrogen. There is also:
  - A large inventory of C-14 within the fuel matrix but this is retained within the fuel and does not contribute to the discharges of the NPP.
  - A negligible production of C-14 coming from the activation of zinc acetate (1-2x10<sup>-4</sup>% of the C-14 coming from the other sources).
- Considering the realistic assumption of 10 mg/kg of dissolved nitrogen in the primary coolant, the UK EPR annual production rate of C-14 is assessed as 444 GBq/year.
- This C-14 source term will be discharged in gaseous, liquid, or solid wastes. Feedback from the discharges of existing plants shows that the repartition of the C-14 source term in the effluent is the following:
  - Around 80% in gaseous releases;
  - Around 5% in liquid discharges;
  - Around 15% in solid wastes.
- International feedback analysis, together with thermodynamic studies, has shown that the main forms of C-14 in the primary coolant are:
  - methane during power operations;
  - CO<sub>2</sub> and HCO<sub>3</sub><sup>-</sup> during outage.
- The presence of acetate (following zinc injection) is not expected to modify the above speciation and it will be removed without significant impact on purification systems, gas and liquid effluents, or solid wastes.
- H-3, tritium, is the most important ternary fission product. However, tritium cannot be used as a fuel failure indicator because:
  - Its production in the primary coolant is predominantly due to boron (86% from B-10 (n,2α)→H-3) and the lithium activation (14% from Li-6 (n, α)→H-3 ; 1% Li-7 (n, αn)→ H-3), independently of the presence, or not, of fuel failures<sup>3</sup>. Minimisation of tritium production is obtained through the use of lithium hydroxide, isotopically enriched in lithium-7 and by limiting the maximum total concentration at the beginning of the cycle.

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<sup>3</sup> Other sources of tritium in primary coolant are deuterium activation (1% from H<sub>2</sub> (n,γ)→ H<sub>3</sub>) and eventual leaking from secondary neutron sources.



- The feedback analysis shows that a defect onset does not induce a step in the tritium activity in the primary coolant. The significant affinity between tritium and zirconium and the consequent low tritium diffusivity through the cladding explain the absence of correlation between the tritium activity in the primary coolant and the presence of fuel failures.
- It is not a gamma emitter and its detection should be performed by beta analysis techniques.

Even if tritium activity does not provide any useful information regarding fuel cladding diagnosis, regular monitoring of tritium in the primary coolant and the fuel pool should be performed in order to prevent any possible increase in the discharges (gas or liquid effluents).

For the UK EPR a limit value will be specified in the fuel pool. A preliminary value of 3000 MBq/t has been defined and the feasibility of applying this value is supported by the following justifications and conclusions [Ref-1]:

- NPP feedback and good practices;
- Coolant Storage and Treatment System (TEP [CSTS]) design and operation;
- primary coolant conditioning;
- dose evaluation allowing the exposure of workers to tritium evaporated from the pools to be minimised;
- simulations providing parametrical estimation of tritium discharged.

The control of these isotopes requires chemical separation and specialised beta or alpha counting devices. Therefore, the routine measurements in the plant cannot be ensured by the chemistry laboratory. However, specific measuring programmes will need to be implemented in order to determine the baseline values and track the activity trends to:

- Establish the typical ratios and spectrum of solid wastes;
- Anticipate the actions to avoid activity increase in liquid and gas effluents;
- Determine the transport conditions in case of packages containing alpha emitters following the fissile material dissemination in the primary coolant.

#### **1.2.5.5. Radiation Field Monitoring**

Amongst the radionuclides monitored for safety consideration, material degradation, and environmental impact, those whose radiological impact is considered dominant due to their main gamma energy should be highlighted. Those radionuclides are Co-58, Co-60, Sb-122, Sb-124, and Ag-110m.

Note that the main nuclides produced from water activation are N-16 and N-17, which are produced from O-16 and O-17. However, due to their short half-lives (7 seconds and 4 seconds), it is not useful to monitor them in the primary system, and their discharges to the environment will be insignificant. However, these isotopes can have an impact on worker doses. On one hand N-16 is a powerful gamma emitter which represents the main radioactive source for external exposure to workers during operation of the reactor. On the other hand the N-17 decays in a few seconds to an excited state of the O-17, which tends to emit neutrons. This nuclide must be taken into account for operator accessibility at full power as an additional source of neutrons (with respect to those from the core).

**1.2.6. Evidence Supporting the Impurity Management of the UK EPR**

The required primary and auxiliary system water quality should be maintained during the different phases of operation and outages throughout plant life. These conditions are those that enable the claims identified for the UK EPR to be achieved.

The chemical conditions of the primary coolant and auxiliary water should verify the necessary requirements to ensure the complete control of the potential impact associated with these impurities.

**1.2.6.1. Identification and Quantification of Evidence**

Impurities in the primary coolant and auxiliary water resulting from release of material due to wear and the external ingress of make-up water can induce several issues. The evidence justifying the effect of these impurities is based on laboratory tests performed under comparable conditions to those of the primary coolant. Based on the elements provided [Ref-1], the impurities and their possible consequences are summarised in the table below.

For the auxiliary systems, two types of risks can be distinguished:

- The direct risks due to the potential corrosion phenomenon affecting the material of each system.
- The indirect corrosion risks for the RCP [RCS] or the other auxiliary systems in interface.

Impurities	Justification	General Corrosion	Cladding Corrosion	CRUD Deposit	SCC (material)	Pitting Corrosion	Mechanism and Other Identified Risks
Fluoride Chloride	Laboratory tests		X (Zirconium Alloy)		X (Austenitic steel)	X (Austenitic steel)	
Sulphates	Laboratory tests				X		Acidification of the environment confined areas → production of reduced species

Impurities	Justification	General Corrosion	Cladding Corrosion	CRUD Deposit	SCC (material)	Pitting Corrosion	Mechanism and Other Identified Risks
Calcium Magnesium Aluminium Silica	Laboratory test Experimental reactors Calculations		X (linked to deposition)	X			Zeolites formation and deposition → heat transfer limitation
Suspended particulates	NPP feedback Laboratory tests		X (linked to deposition)	X			CRUD deposition → fuel pool contamination Turbidity of pools
Nickel	NPP feedback Laboratory tests		X (linked to deposition)	X			
Sodium (caustic conditions at high temperature)	Laboratory tests	X					Radiation due to the activation of Na-23 into Na-24
Oxygen	Laboratory tests NPP feedback Calculations	X	X	X	X	X	C-14 formation due to the activation of O-16

**1.2.6.2. Mitigation Actions Implementation**

Impurity concentrations in the RCP [RCS] and in the auxiliary systems should be kept to a practical and achievable minimum. With the objective of reducing the amount of impurities in the primary circuit and auxiliary systems, different optimisations can be applied:

- Impurity source term minimisation for improvement of the make up water quality and the characteristics of filters (without silica).
- Control of the impurity concentration through the application of limits (section 3) and due to the purification function present in different systems: RCV [CVCS], fuel pool, TEP [CSTS], demineralisers, etc.

- **Oxygen and hydrogen limitation:** The oxygen and hydrogen gas fractions are limited in biphasic tanks (RPE [NVDS], TEP [CSTS], REA [RBWMS], RCV [CVCS], REN [NSS], PRT) due to continuous nitrogen flushing from the TEG [GWPS], ensuring  $O_2 < 2\%$  and  $H_2 < 4\%$  under normal operating conditions. The oxygen and hydrogen removed from biphasic tanks by nitrogen flushing are collected in the TEG [GWPS] loop where the risk of flammability is avoided by the use of a recombiner (leading to water production by hydrogen/oxygen recombination). After recombination, the  $H_2$  and  $O_2$  concentration in the flushing gas ( $N_2$ ) is approximately 0.0 - 0.3%  $H_2$  by volume and approximately 0.0 - 0.1%  $O_2$  by volume.
- **Anti-carbonation means** have been implemented in order to avoid water carbonation in the auxiliary systems in contact with air and conditioned with alkaline additives to reduce material corrosion;
- **Impurity transfer limitation:** The absence of accumulation is accentuated by the application of the boron recycling strategy. However, the UK EPR design includes a number of measures for minimising the transfer of radioactivity and impurities between the different auxiliary systems and the subsequent progressive accumulation of activated or non-activated impurities, with associated radioprotection and/or material integrity consequences. The main measures applied to avoid impurity transfer are:
  - Collection of filtered drains in the RPE [NVDS]
  - Automatic and manual control of TEP1 [CSS] storage tanks
  - Installation of a mechanical filter downstream of RPE [NVDS] before the drain transfer toward the TEP [CSTS] effluent tanks.
  - Installation of several, redundant sampling locations, on-line devices and instrumentation and control measures to ensure the impurity concentration monitoring as well as the control of parameters having an influence on their behaviour (temperature, pressure, flow rates), [Ref-1] [Ref-2]
  - Implementation of Discharge Process Selection: the feasibility of selecting a suitable process for discharging or recovering the distillates and/or the concentrates depending on compliance with the chemistry /radiochemistry specifications. The distillates/concentrates are tested before being re-injected into the primary coolant via the REA [RBWMS] and then the RCV [CVCS]. In the event that chemistry and/or radiochemistry criteria are not fulfilled, the distillates/concentrates are routed towards the TEU [LWPS], via the RPE [NVDS], to be treated as effluents.
  - Viability of complete drainage of the IRWST: In the event of pollution of the water in the IRWST, it may be necessary to completely drain the tank, and then fill it with clean borated water. For preventive surveillance, the IRWST water quality is regularly monitored for compliance with chemistry/radiochemistry specifications and if the criteria are not met, the polluted water is drained into the TER [ExLWDS] tanks, via the PTR [FPCS] pumps, with or without the use of a purification chain, depending on the circumstances. Furthermore, complete drainage may also be necessary in the case of an IRWST inspection, in which case, the borated water is stored in another compartment, so that it can be re-used.

Details concerning all of the criteria monitored in the different circuits are provided in section 1.2.9, while the sampling and measurement techniques are described in supporting documentation [Ref-1].

**1.2.7. Evidence supporting the Chemical and Radiochemical Purification of the Primary Circuit of the UK EPR**

As established by the overall methodology for activity management of the UK EPR, the treatment system has been designed taking into account the expected activity characteristics of the primary circuit: soluble, particulate, gas, and volatile.

**1.2.7.1. Identification and Quantification of Evidence**

The operating treatment systems (RCV [CVCS], TEP [CSTS] and PTR [FPCS]) [Ref-1] to [Ref-4] have been established to ensure the best water conditions in the primary coolant and fuel pools in order to avoid potential issues concerning particulate and CRUD deposition.

In order to follow the purification system performance, decontamination factors (DF) are followed. They are calculated as the ratio of the initial amount of a nuclide in a stream to the final amount of that nuclide in a stream following treatment by a given process. The decontamination factors represent the expected equipment performance averaged over the life of the plant.

Feedback shows that the performance of filter and resins ensures higher decontamination factors for those nuclides taken into account in the source term definition. The reference values retained for the UK EPR are in agreement with international guidelines (see the table below). The monitoring of decontamination factors is included in the laboratory activities of the plant and the state of demineralisers is routinely checked in case of an abnormal change in DF.

<b>Chemical Species</b>	<b>DF for UK EPR Demineralisers</b>
Iodines	100 - 10000
Caesium - strontium	1.2 / 2 - 5
Corrosion products	10 - 100
Ag-110m	10
Antimony	10 - 100

**Decontamination Factors retained for UK EPR [Ref-3] [Ref-5]**

The decontamination factors are regularly monitored by chemistry staff of the plant undertaking activity measurements upstream and downstream of the demineralisers. When the expected change in decontamination factors is not observed, corrective actions are applied (flow rate verification, filter replacement, resin verification, etc.).

**1.2.7.2. Purification Implementation of the UK EPR**

The online primary coolant purification coming from RCV [CVCS] is ensured by the letdown line going successively through:

- Two upstream redundant low mesh mechanical filters (1 µm threshold) to remove suspended solids permanently in the primary coolant (each filter is used alternatively with each one capable of treating 100% of the flow);

- One mixed bed ion exchanger in lithium form, to remove dissolved impurities permanently in the primary coolant, without eliminating lithium in the primary coolant.

Additionally following purification, further measures are available on the UK EPR:

- Another mixed bed ion exchanger in H<sup>+</sup> form, is aligned, downstream of the RCV [CVCS], to the TEP1 [CSS] storage tanks:
  - to remove and recover lithium: when saturated with lithium, this demineraliser will be exchanged and aligned to the RCV [CVCS] letdown line [Ref-1];
  - to obtain a polished purification to eliminate residual soluble impurities in the primary effluent prior to transfer to the coolant storage tanks TEP1 [CSS], and prior to evaporation treatment.
- A mixed bed demineraliser upstream of TEP [CSTS] evaporator to mitigate any risk of pollution of the primary effluent prior to treatment in the evaporator.
- A monitoring of gross gamma activity in the REA [RBWMS] boric acid make-up tank samples in order to:
  - detect any contamination;
  - make sure that the above purification devices operate correctly.
- The PTR [FPC(P)S] is used to:
  - purify the pools in the reactor building, fuel building, and the IRWST (in particular, to control radioactivity with its demineraliser and filters);
  - skim the spent fuel pit and reactor cavity, which helps to control radioactivity and visibility for fuel handling.

The above measures ensure that the required quality of coolant is obtained, consistent with the ALARP principle [Ref-2] and [Ref-3].

### **1.2.8. Evidence supporting the Shutdown and Start-up Procedures of the UK EPR**

During shutdown and start-up phases the physicochemical conditions of the primary coolant are drastically modified: pH, redox potential, temperature, and pressure. These modifications affect the radionuclide and corrosion product solubility, and fission product release. The shutdown and start-up strategy applicable to the UK EPR has been established taking into account the specific UK EPR requirements and international guidelines.

The primary goal of shutdown and start-up guidelines is to properly manage the radionuclide and chemical activities in order to minimise the consequences on radiation fields, fuel integrity monitoring, H-2/O-2 hazardous mixtures, material performance, and effluent and waste production.

### 1.2.8.1. Identification and Quantification of Evidence

Achievement of established control goals during **shutdown** is based on the following principles:

- **pH control optimisation in order to:**
  - maintain the optimum  $\text{pH}_T$  during the hot shutdown period; .
  - reach the acid conditions during boration to allow an increase in the solubilisation of core deposits (especially during the oxygenation phase to remove the maximum amount of deposits);
  - mitigate the potential iodine risks (absorption and volatilisation) and potential antimony contaminations;
  - avoid any practice that could increase the lithium concentration in the coolant and lead to an increase in  $\text{pH}_T$  during shutdown (which can imply corrosion product re-deposition).
- **H<sub>2</sub> concentration optimisation in order to:**
  - ensure the absence of a H<sub>2</sub>/O<sub>2</sub> mixture in the gaseous phase;
  - maintain reducing conditions during the cooling phase (before pressuriser bubble collapsing) to minimise the solubility of activated corrosion products and therefore the risks of recontamination of the RCP [RCS];
  - minimise the effect of oxygen ingress at the RIS/RRA [SIS/RHRS] connection;
  - minimise the risks of Low Temperature Crack Propagation (LTCP) at temperatures lower than 150°C.
- **Fission product monitoring in order to:**
  - optimise the effluent management;
  - plan sipping tests;
  - anticipate the radiochemical risks (for instance: iodine-alpha risk) during outage operations and plan the implementation of preventive actions.
- **O<sub>2</sub> concentration control in order to:**
  - avoid any risk of a H<sub>2</sub>/O<sub>2</sub> mixture (gaseous phase);
  - minimise the risk of SCC;
  - minimise the activity increase in the primary coolant before the oxygenation phase with a possible impact on surface contamination.
- **Corrosion product control and reactor coolant pump operations control in order to:**
  - minimise the surface contamination to limit the dose received during human intervention;

- maintain a mass flow through the core to enhance dissolution of corrosion products and CRUD burst releases;
- limit particulate activity deposition, especially in the loops where steam generator inspections are planned in order to minimise the contamination in these steam generators and facilitate inspection activities.
- **Maximise the clean-up capabilities in order to:**
  - maintain low levels of impurities in the primary coolant and auxiliary circuits such as TEP [CSTS] and REA [RBWMS] boric acid make up tanks;
  - minimise the corrosion product deposition in the circuits;
  - favour core deposit elimination in the primary coolant by retention in demineralisers.

The following table summarises the principles that govern shutdown and the associated claims.

Shutdown Principles	Claims
pH control	Radioprotection / core deposit
H <sub>2</sub> control	Safety / Material Integrity / Radioprotection
O <sub>2</sub> control	Safety / Material Integrity
Fission product control	Fuel Integrity monitoring / Availability / Effluents / Radioprotection
Corrosion product control / Reactor coolant pumps operation / Clean-up	Radioprotection / Fuel deposit

**Shutdown Principles and Associated Claims**

The achievement of established control goals during **start-up** is based on the following principles:

- **Reactor coolant filling optimisation in order to:**
  - remove the air pocket accumulated in the highpoint of the primary circuit (pressuriser vessel, reactor vessel head, and upper portions of the steam generator tube bundles);
  - control SiO<sub>2</sub> concentration in the filling water;
  - limit O<sub>2</sub> ingressions;
  - limit impurity concentrations in filling water.
- **Optimisation of O<sub>2</sub> elimination in order to:**
  - ensure the absence of oxygen in the primary circuit before beginning H<sub>2</sub> injection;
  - minimise the risk of SCC;



- reduce critical path time;
- limit CRUD burst.
- **pH control optimisation in order to:**
  - ensure that the minimum  $pH_T$  selected for the plant optimised programme is achieved ( $pH_{300^\circ C}$  of 7.2) prior to producing heat from the core;
  - minimise deposition of corrosion products on the fuel and radiological issues.
- **H<sub>2</sub> concentration optimisation in order to:**
  - prevent the formation of H<sub>2</sub>/O<sub>2</sub> mixtures;
  - reach the reducing conditions before the reactor becomes critical;
  - prevent the fuel hydriding risk;
  - reduce the probability of nickel metal deposition.
- **Fission product monitoring in order to:**
  - detect fuel failure onset from the beginning of the cycle;
  - apply the adapted radiochemical specifications.
- **Corrosion product monitoring in order to:**
  - adapt the purification conditions and improve the resin management, in order to:
    - limit the deposit formation and limit AOA/CIPS risk during cycle operation;
    - mitigate the recontamination risks upon heating (inverse solubility of radionuclides).

The following table summarises the principles that govern the start-up and the associated claims [Ref-1].

<b>Start-up Principles</b>	<b>Claims</b>
Reactor coolant filling optimisation	Safety / Contamination / Integrity Materials
H <sub>2</sub> control	Safety / Material Integrity / Radioprotection / Fuel Deposit
O <sub>2</sub> control	Safety / Material Integrity
pH control	Radioprotection / Contamination / Material Integrity
Fission product control	Fuel Integrity monitoring / Availability
Corrosion product control	Radioprotection / Fuel CRUD

**Start-up Principles and Associated Claims**

### 1.2.8.2. Implementation of Shutdown / Start-up Strategy

The achievement of objectives established for shutdown and start-up are ensured for the UK EPR by the application of:

- Chemical and radiochemical specifications;
- Shutdown and start-up procedures [Ref-1].

The REN [NSS] of the UK EPR is equipped with measurement techniques adapted to monitor the radionuclides and chemistry parameters identified, to ensure the control of safety, fuel, material, radiation fields and operational availability for the UK EPR as well as the prevention of discharges to the environment.

### 1.2.9. Evidence supporting the Chemistry and Radiochemistry Monitoring

The REN [NSS] system of the UK EPR is equipped with measurement techniques adapted such that monitoring of the radionuclides and chemistry parameters is achieved for ensuring the control of safety, fuel, material, radiation fields, environment and operational availability of the UK EPR.

The REN [NSS] has the main task of centralising, for analysis and determination of chemical and radiochemical characteristics, the liquid samples collected in the following systems:

- Reactor Coolant System (RCP [RCS]);
- Residual Heat Removal System (RRA [RHRS]) during shutdowns;
- Chemical and Volume Control System (RCV [CVCS]);
- Safety Injection System (RIS [SIS], IRWST);
- Coolant Treatment System (TEP3/5/6 [CTS]);
- Fuel Pool Cooling (and Purification) System (PTR [FPC(P)S]);
- Reactor Boron & Water Makeup System (REA [RBWMS]);
- Nuclear Vent and Drain System (RPE [NVDS]).

In addition to the identified items, the REN [NSS] has some additional objectives contributing to safety. The control parameters associated with each objective are listed in the table below. The monitoring of these parameters allows evaluation of the primary circuit state and provides an alert regarding its potential degradation (fuel cladding performance, material integrity, pollution and impurity intrusion) and its possible impacts on radiation fields, effluents or waste.

	<b>REN [NSS] Objectives</b>	<b>Parameters Monitored</b>
Main Objective	To centralise samples for chemical and radiochemical characteristics analysis and determination	Determination of <b>activity and/or concentration of substances (Si, O<sub>2</sub>, H<sub>2</sub>, Li, Ca, Al, Mg, Na, NH<sub>3</sub>, sulphate, phosphate, chloride, fluoride, zinc, nickel)</b> present in the fluid contained in the primary circuit and auxiliary systems (RRA [RHRS], RCV [CVCS], RIS [SIS], IRWST, TEP3/5/6 [CTS], PTR [FPC(P)S])
Additional Objectives Linked to Safety	To contribute to the control of the reactivity	<b>Boron monitoring</b>
	To contribute to the containment of radioactive substances, i.e., isolation, fission products containment, etc.	Monitoring and analysis of <b>fission product activity</b> in order to evaluate fuel cladding failures
		Evaluation of <b>corrosion product</b> activity in order to minimise the radioactive waste
	To contribute to operational objectives	Evaluation of <b>primary activity</b> (by KRT [PRMS] measurement) in order to detect high levels in reactor coolant
Detection of filter and resin anomalies ( <b>activity and concentration measurement upstream or downstream</b> )		
		Detection of potential material degradation provoking the increase of a determinate parameter: <b>Co, Sb, Ag, etc.</b>

**1.2.9.1. Sampling Implementation for the UK EPR Primary and Auxiliary Circuits**

The sampling equipment has been designed considering the following principles:

- The compliance of functions associated with the REN [NSS];
- The representative sampling;
- The sampling site conditions;
- The dose rates during sampling;
- The frequency of sampling;
- The number and the type of analysis requested.

Normal chemical / radiochemical laboratory analytical techniques will be used for the UK EPR [Ref-2]

For each system, the following items are described [Ref-1]:

- The sample locations;
- The parameters monitored;
- The techniques of analysis required to monitor the indicators selected to ensure the optimal chemistry and/or radiochemistry monitoring for the UK EPR;
- The frequencies of measurement and the range of expected values.

The tables below list for each system the parameters monitored [Ref-2].

**Chemical Parameters to be monitored as function of Systems [Ref-2]**

Origin	Parameter	RCP [RCS]	RCV [CVCS]	TEP [CSTS] (Distillate)	TEP [CSTS] (concentrates) REA [RBWMS] Boron	RIS [SIS]	RA [RHRS] connected	Reactor Pool	Fuel Pool	IRWST	RBS [EBS]	TEG [GWPS]	RPE [NVDS]	RRI [CCWS]	SED	EVU [CHRS]	TEU [LWPS] demin	TEU [LWPS] concentrates
Primary coolant additive (Parameter to be controlled)	Enriched Boric Acid [B]	X	X		X	X	X	X	X	X	X						X	X
	Enriched Boric Acid ( <sup>10</sup> B (at%))	X	X		X	X		X	X	X	X							
	Hydrogen [H <sub>2</sub> ]	X	X				X											
	Lithium Hydroxide [Li]	X	X				X											
	Depleted Zinc Acetate ([Zn])	X	X															
	Hydrazine	X					X											
	Hydrogen Peroxide	x					X											
Auxiliary Additives	Trisodium Phosphate													X		X		
	Sodium Hydroxide															X		

X indicates that the criteria should be verified.

**Chemical Parameters to be monitored as function of Systems (cont'd) [Ref-2]**

Origin	Parameter	RCP [RCS]	RCV [CVCS]	TEP [CSTS] (Distillate)	TEP [CSTS] [concentrates] REA [RBWMS] Boron	RIS [SIS]	RA [RHRS] connected	Reactor Pool	Fuel Pool	IRWST	RBS [EBS]	TEG [GWPS]	RPE [NVDS]	RRI [CCWS]	SED	EVU [CHRS]	TEU [LWPS] demin	TEU [LWPS] concentrates	
Impurities	Oxygen	X		X	X		X												
	Chloride	X	X		X	X	X	X	X	X	X			X	X	X		X	
	Fluoride	X	X		X	X	X	X	X	X	X			X	X				
	Sulphate	X	X		X	X	X	X	X	X	X				X				
	Phosphate	X	X															X	
	Silica	X			X	X	X	X	X	X	X				X				
	Calcium	X			X	X	X		X	X	X			X			X	X	
	Aluminum	X			X	X	X		X	X	X								
	Magnesium	X			X	X	X		X	X	X								
	Sodium	X	X		X			X	X	X	X							X	X
	Conductivity			X											X				
	H <sub>2</sub> gas (%)		X									X	X						
	O <sub>2</sub> gas (%)											X	X						
	pH <sub>25°C</sub>	X													X				
	Suspended Solids														X	X			
Iron														X					

X indicates that the criteria should be verified.

**Radiochemistry Parameters to be monitored in Auxiliary Systems during Normal Operation [Ref-2]**

Parameter	RCP [RCS]	RCV [CVCS]	TEP [CSTS] (Distillate)	TEP [CSTS] (concentrates) REA [RBWMS] Boron	RIS [SIS]	RA [RHRS] connected	Reactor Pool	Fuel Pool	IRWST	RBS [EBS]	TEG [GWPS]	RPE [NVDS]	RRI [CCWS]	SED	EVU [CHRS]	TEU [LWPS]
Spectrometry gamma	X	X	X		X	X	X	X	X	X			X			X
Gamma Total	X	X	X		X		X	X	X	X	X		X			X
Tritium	X					X	X	X					X			X

X indicates that the criteria should be verified.

**Radiochemistry Parameters to be monitored in Auxiliary Systems during Shutdown [Ref-2]**

Phase shutdown	Radionuclide				
	Xe-133	I-131	Co-58	γT	H-3
Before shutdown	X	X	No particular requirement		
Before H <sub>2</sub> O <sub>2</sub> injection for oxygenation	No particular requirement		No particular requirement		
Stop last Main Reactor Coolant Pump	X	X	X	X	No particular requirement
End of N <sub>2</sub> flushing (switch TEG [GWPS] → EBA [CSVS])	X	X	No particular requirement		
End of air RCP [RCS] flushing (3/4 loops)	X	X	No particular requirement		
Before RPV integrity breakdown	X	X	No particular requirement		
Before Reactor Building pool filling	Monitoring without particular requirement	Monitoring without particular requirement	X	X	X



**1.3. EVIDENCE SUPPORTING THE CLAIMS IDENTIFIED FOR UK EPR**

The arguments mentioned in section 1.1 to demonstrate that the associated claims are valid have been grouped under each claim in the tables below. Each argument is directly followed by the relevant evidence ensuring that the claims defended for the UK EPR, are based on tangible arguments. The specific evidence supporting a particular claim has also been provided.

**1.3.1. Evidence Supporting the Claim: Safety**

Claim	Arguments	Evidence	Section describing the claim
Safety	Boron Strategy	Management and Control of EBA use by applying specific enrichment and storage procedures defined according to a risk analysis	1.2.1
		Boron-10 isotopic monitoring and depletion determination for process control	1.2.1
		Total boron concentration monitoring for pH control	1.2.1
	Flammability risk management	On line H <sub>2</sub> – O <sub>2</sub> monitoring in primary coolant	1.2.9
		H <sub>2</sub> gas O <sub>2</sub> gas measurement in biphasic system components	1.2.9
		TEG [GWPS] design: <ul style="list-style-type: none"> <li>- Recombiner to ensure H<sub>2</sub> &lt; 0.3%, O<sub>2</sub> &lt; 0.2% in TEG [GWPS] flow</li> <li>- N<sub>2</sub> continuous swept to ensure (H<sub>2</sub> gas &lt; 4%, O<sub>2</sub> gas &lt; 2%) in biphasic capacities</li> </ul>	1.2.4
		Shutdown procedure optimisation: <ul style="list-style-type: none"> <li>- Hydrazine injection at RIS/RRA [SIS/RHRS] connection</li> <li>- Physical degassing: TEP4 [CDS], PZR-RPE [NVDS]</li> <li>- Chemical Dehydrogenation</li> </ul>	1.2.8.1
		Start-up procedure optimisation: <ul style="list-style-type: none"> <li>- Physical degassing: TEP4 [CDS],</li> <li>- Hydrazine injection</li> </ul>	1.2.8.1
	Initial conditions for radiological consequences studies during accidents	Specification of : <ul style="list-style-type: none"> <li>-Eq. I-131 in RCP [RCS] during transient periods</li> <li>-ΣGas in RCP [RCS] during full power operation.</li> <li>- Eq. I-131 in RCP [RCS] during outages</li> </ul>	1.2.5.1.

Claim	Arguments	Evidence	Section describing the claim
	Iodine volatilisation	Injection of NaOH into EVU [CHRS] tanks with the specification of: <ul style="list-style-type: none"><li>- Maximum NaOH concentration to achieve alkaline conditions in the IRWST in order to limit the volatile iodine in the containment during LOCA or severe accident.</li><li>- Minimum NaOH concentration to avoid crystallisation in tanks</li></ul>	1.2.5.1
	Control of the nuclear island containment barriers integrity in short term	Xe-133 activity in the RCP [RCS] during normal operation Xe-133/Xe-135 in the RCP [RCS] during normal operation	1.2.9.1

**1.3.2. Evidence Supporting the Claim: First Barrier Integrity**

Claim	Argument	Evidence	Section describing the claim
First Barrier Integrity	<b>CRUD Deposition Optimisation By:</b>		
	pH control	Solubility control contribution to limiting the corrosion product transfer	1.2.2
	Zn injection	Source term reduction contribution to generalised corrosion reduction	1.2.3
	Impurity limitations	Ni and Ca, Al, Mg specifications contribution to limit corrosion products and Zeolites deposition	1.2.6
	Gadolinium	Boron concentration reduction contribution to borate reduction deposition	1.2.1
	<b>Corrosion Limitation By:</b>		
	Fuel cladding material choice	M5 Alloy : General corrosion reduction	1.2.4.1.1
	Fuel failure monitoring	Detection and characterisation of fuel failure Xe-133/Xe-135, Cs-134/Cs-137, Xe-135/Kr-85m	1.2.5.2

**1.3.3. Evidence Supporting the Claim: Integrity of Second Barrier**

Claim	Argument	Evidence	Section describing the claim
Integrity of second barrier	Good performance of Alloy 690 under primary coolant conditions	Good performance of Alloys 690/152/52 Normal impurities control (sulphate, fluoride, chloride, oxygen)	1.2.3.1 and 1.2.4.1.1 1.2.5.5
	Primary to secondary leaks	N-16 measurement in the main steam line	1.2.5.3

**1.3.4. Evidence supporting the Claim: Radiation Field Reduction**

Claim	Argument	Evidence	Section describing the claim	
Radiation Field Optimisation	pH optimisation	Solubility control → Transfer corrosion products test, OPEX, Modelling	1.2.2.1.2	
	Zinc injection	General corrosion reduction, surface passivation Co inhibition/replacement test, OPEX, Modelling	1.2.3	
	Control of H <sub>2</sub> concentration to limit nickel in the core	Thermodynamic calculations	1.2.4.1.3	
	O <sub>2</sub> RCP [RCS] ingress limitation through REA [RBWMS] boron make-up	REA [RBWMS] tanks swept by the TEG [GWPS] (Evaporation, degassing, H <sub>2</sub> recombination in TEG [GWPS])	1.2.6.2	
	Material Selection by avoiding use of grade with activable element – ALARP approach	Ni reduction with the choice of Alloy 690 (laboratory tests) Co reduction with Stellite replacement according to an ALARP approach		1.1.4.1
			Ag (replacement when possible of seal coated with silver)	1.1.4.1
			Sb (seals, rotors, bearings)	
	Fabrication processes	Optimisation of Alloy 690 manufacturing	1.1.4.1	
	Purification Optimisation	Dedicated demineraliser PTR [FPC(P)S] purifications High RCV [CVCS] flow rate	1.2.7	
Transient periods optimisation	Shutdown and start-up procedures	1.2.8		

**1.3.5. Evidence supporting the Claim: Measurement Accuracy**

Claim	Argument	Evidence	Section describing the claim
Measurement Accuracy	Design REN [NSS]	Representative sampling location	1.2.9
		Available techniques	1.2.9
		Equipment locations	1.2.9
	Measurement Frequencies	Online control	1.2.9
		Frequencies imposed by Chemical and Radiochemical Specifications	1.2.9

**1.3.6. Evidence supporting the Claim: Limit Impact on Environment**

Claim	Argument	Evidence	Section describing the claim
Limit Impact on Environment	Zinc injection	Liquid effluents and solid waste reduction by source term reduction (general corrosion reduction)	1.2.3
	Tritium management	Good practice application Limits proposed	1.2.5.4
	Carbon management	Thermodynamic calculations Open point	1.2.5.4
	Noble Gas Management	Limits $\Sigma$ Gas specifications	1.2.5.4
		Delay Beds	1.2.5.4
	Iodine Management	Limit Eq. I-131 specification	1.2.5.4
		Thermodynamic calculations → Chemistry optimisation	1.2.5.4
		Filter iodine incorporation	1.2.5.4
	Fissile Material Consideration	Limit I-134 specification	1.2.5.1 & 1.2.5.2

Claim	Argument	Evidence	Section describing the claim
		Alpha Activity monitoring	1.2.5.2
		Thermodynamic calculations → Chemistry optimisation	1.2.5.4

**1.3.7. Evidence supporting the Claim: Operating Unit Availability**

Claim	Argument	Evidence	Section describing the claim
Improvement of Plant Operating Availability		Radiochemistry monitoring, in particular Ni, Co, Cr monitoring	1.2.9
		Chemistry monitoring, Li	1.2.9 1 & 1.2.2.2
		Flux map analysis	1.1.7
		Code calculations	1.1.7 & 1.2.2.1.2
	Fuel failure management	Use of radiochemistry specifications	1.2.9 & 1.4
		Application of Shutdown procedures	1.2.8
		Primary coolant activity monitoring and analysis	1.2.9
		Support of modelling evaluations during the cycles	1.2.5.2
	RCP [RCS] material resistant to corrosion	Use of material resistant to corrosion: Alloy 690TT and Stainless Steel	1.2.3.1 and 1.2.4.1.1



#### 1.4. IDENTIFICATION AND CLASSIFICATION OF CHEMICAL AND RADIOCHEMICAL PARAMETERS

The classification of chemical parameters can be performed from the below listed criteria:

- As a function of the applicability of the parameters:
  - Control parameters having a direct link with the mitigation and control of the consequence on safety, radiation fields, environment, aggression, maintenance and operation issues. These parameters are associated with a limit value of which violation implies that a procedure will be utilised.
  - Complementary parameters which assist chemistry staff in interpreting variations in the system chemistry.

This final classification will be defined in the applicable operating procedures.

- As a function of the domain:
  - safety and material integrity;
  - environment;
  - plant availability.
- Based on the elements provided in the previous paragraphs, the values associated with each parameter are the result of several compromises between the risks and the benefits associated with the different parameters during the various conditions of operation. The table in section 3 provides **preliminary values** for these parameters. The justification of the values is provided taking into account the balance between the positive and negative effects according to NPP feedback, test laboratories, and/or modelling evaluations.
- The final numerical values will be defined by the operator in the operating procedures of the UK EPR.

The table below provides the listing of influential parameters in the primary circuit where each parameter is reported as a function of its classification and domain.

		<b>Control Parameter</b>	<b>Complementary Monitoring Parameter</b>
Domain	Safety	B-10 and Total Boron concentration Eq. I-131 $\Sigma$ Gas	Boron isotopy
	Material Integrity (corrosion not due to the CRUD)	Hydrogen concentration Oxygen concentration Lithium concentration Chlorides, Fluorides, Sulphates and Sodium concentrations Xe-133 Xe-133/Xe-135	Eq. I-131 I-134
	Radioprotection / Contamination / CRUD Management	Hydrogen concentration Lithium concentration** Zinc concentration Nickel concentration Silica concentration Eq. I-131 I-134	Calcium, Magnesium, Aluminium concentration Gamma spectrometry Global Gamma Global alpha Alpha spectrometry Tritium activity
	Environment	Xe-133	Nitrogen* concentration Tritium activity
	Operational Availability	Hydrogen concentration* Oxygen concentration* Lithium concentration**	Nitrogen* concentration Ammonia concentration

\* also in gas phase

\*\* for pH management

**Primary and Auxiliary Chemistry Parameters – Monitoring during Normal Power Operation**

## 2. SECONDARY SIDE SYSTEM WATER CHEMISTRY

### 2.1. CLAIMS AND ASSOCIATED ARGUMENTS

The claims associated with the management of the secondary coolant chemistry are the following:

- To contribute to achieving the fundamental safety functions by:
  - maintaining the Steam Generator (SG) cooling function of the primary coolant circuit;
  - maintaining the integrity of the second barrier (the reactor coolant pressure boundary);
- To contribute to limiting the impact on the environment;
- To ensure optimal sampling;
- To improve plant performance: Plant Operating Availability.

The above claims are justified by several arguments developed in the following sections of this sub-chapter. In some cases an argument will support several different claims.

#### 2.1.1. Contribution to Safety Functions

##### 2.1.1.1. Integrity of Second Barrier

Ensuring the integrity of the reactor coolant pressure boundary consists of avoiding SG tube failure and activity release into the secondary coolant. Accordingly, the second barrier integrity is ensured by:

##### SG design:

The SG material selection decreases the risk of SG tube failure because:

- The choice of the SG tube material (Alloy 690TT) exhibits superior secondary side Stress Corrosion Cracking (SCC) resistance to all other candidate steam generator tube alloys [Ref-1].
- The Tube Support Plate (TSP) design is a high permeability TSP fabricated from stainless steel, which limits the risk of TSP corrosion and sludge deposit. The high permeability increases the recirculation ratio which is beneficial for the reduction of sludge deposits on the TSP and limits the risk of corrosion on the top of tubesheet [Ref-1].

Secondary System Materials:

The choice of material resistant to FAC in the secondary system is one containing a sufficient amount of chromium as an alloying metal, which limits iron ingress into the SG and thus the formation of deposits where impurities could concentrate.

Secondary Chemistry during Normal Operation:

The choice of alkaline and reducing media during normal operation enables the following:

- Reduction of the risk of both generalised corrosion and FAC leading to minimisation of deposit formation and associated build-up of impurities;
- To avoid oxidising conditions in the SG which are known to be detrimental to localised corrosion;
- Avoid build-up of impurity deposits in the SG, leading to corrosion risk.

The measures implemented for the UK EPR to achieve these conditions are:

- pH optimisation: Optimisation of pH plays an important role in the generalised corrosion and the FAC of carbon steel and/or low alloy steel of the secondary circuit. To mitigate FAC as much as possible in the secondary systems and the transport of corrosion products in the SGs, an optimal pH value has to be defined. pH plays a role in the phenomena of fouling/clogging mechanism. The optimal pH value must also take into account these phenomena.
- Hydrazine, as a reducing agent is added to the secondary system in Pressurised Water Reactor (PWR) plants to minimise material corrosion by limiting the oxygen content, maintaining a reducing potential and corrosion product in a reduced form.
- Limitation of impurities: Localised corrosion such as stress corrosion cracking and/or pitting corrosion depends on impurity concentrations in the secondary water. The impurities in the feedwater and SGs are:
  - Limited by the leak tightness technology of the condenser, the Steam Generator Blowdown (SGBD) purification system, the secondary water pollutants specification (such as sodium, anionic compounds at SGBD, and oxygen of the feedwater)
  - Controlled by continuous on-line monitoring, or grab sample as reported in section 2.1.3
- Transient Optimisation to Limit Pollution Ingress:
  - due to the use of the Start-up Condensate and Feedwater Purification system (ATD), chemical purification will be obtained during start-up [Ref-2];
  - during shutdown the SG lay-up specification has been optimised in order to maintain the SG in a clean state and allow for start-up in good chemical conditions [Ref-1].

### 2.1.1.2. SG cooling function

The design of the SG and secondary circuit associated with the secondary chemistry management contributes to ensuring the primary circuit cooling.

#### SG design:

The design of the SG has been defined to ensure the heat exchange efficiency between the primary and secondary sides as described in Sub-chapter 5.4, section 2.

#### SG and secondary circuit integrity

The structural integrity of the secondary circuit and more specifically of the SG components (shell, tubes...) is crucial to SG cooldown function. Therefore the arguments in support of the integrity of second barrier listed in sub-section 2.1.1.1 also apply in this section.

#### Secondary Chemistry during Normal Operation:

The secondary side chemistry contributes to the safety cooling function of the plant during normal operation through:

- Secondary pH management (control in feedwater and SG) in order to avoid:
  - Generalised corrosion of carbon steel and/or low alloy steel
  - Flow Assisted Corrosion (FAC) which could lead to secondary piping breaks and leaks
  - Localised corrosion (such as stress corrosion, pitting corrosion) of stainless steel, or nickel base alloys in the SG
  - Deposits in the SG where impurities could concentrate and accumulate, leading to corrosion risk
- Limitation of impurities in order to avoid localised corrosion.

#### Choice of Secondary System Material:

Materials containing a sufficient amount of chromium as an alloying metal are chosen in the secondary system to resist FAC. This reduces iron ingress into the SGs and limits the formation of deposits where impurities could potentially concentrate. In addition, the absence of copper alloys enables operation at high pH values, which is beneficial for the limitation of FAC.

### 2.1.2. Optimisation of the Environmental Impacts

Secondary pH<sub>T</sub> selection has been determined in order to limit FAC. Amines have been chosen with respect to the pH selected. Consideration was also given to the environmental impact, i.e. liquid waste discharges and solid waste (APG [SGBS] resin) generation. ATD use at start-up contributes also to effluent reduction.

### 2.1.3. Optimal Sampling

The secondary circuit sampling and monitoring is ensured by the Nuclear Sampling System (RES) [Ref-2] and the Turbine Hall Chemical Sampling System (SIT) [Ref-1] whose designs have been defined as a function of:

- The chemistry parameters to be monitored:
  - Nuclear Sampling System (RES) at SG blowdown: sodium and cation conductivity are measured on line, and grab sampling allow measurements of chlorides, sulphates, silica and suspended solid;
  - Turbine Hall Chemical Sampling System (SIT):
    - pH, O<sub>2</sub>, N<sub>2</sub>H<sub>4</sub>, cation conductivity, iron at SG feedwater;
    - pH, sodium, and oxygen at condensate outlet.
- The available techniques: on line and laboratory measurements;
- The frequency of measurements established by the chemistry specifications according to the phases of operation and the plant operating conditions (in the presence of pollutants).

Measurement accuracy is ensured by an appropriate selection of the location of sampling lines and the location of system components placed to facilitate maintenance and calibration during plant operation.

### 2.1.4. Plant Unit Availability

The issues and maintenance programme having an impact on plant availability are:

- SG tube fouling, TSP clogging, and Tubesheet (TS) fouling;
- Condenser leakage;
- Non Destructive Examination (NDE) tube control;
- Control of sensitive piping to FAC.

For the UK EPR the following measures have been applied:

- The choice of an optimised secondary coolant pH to limit deposit formation and control impurities;
- The SG design: the choice of SG tube alloy with good resistance to corrosion, high permeability of the TSP, and the provisions taken in the design to facilitate inspection and cleaning of affected areas;
- The choice of secondary system material with a sufficient chromium content in order to limit the FAC risk in the secondary system. This limits the iron ingress into the SGs, thus preventing the formation of deposits where impurities could concentrate;

- The use of leak tightness technology of the condenser to limit the ingress of impurities, and the chemical controls at the condenser outlet.

**2.2. SUPPORTING EVIDENCE FOR THE UK EPR**

Evidence supports different arguments and claims. The principles of this evidence are first described in order to underline the operating consequences. Details regarding the justification of these claims and arguments are provided in detailed reports.

Secondly, the arguments mentioned in section 2.1 demonstrate that the associated claim is valid having been grouped under each claim in the tables below. Each argument is directly followed by the relevant evidence ensuring that the claims defended for the UK EPR are based on tangible justification.

Claim	Argument	Evidence	Section describing the claim
Contribution to safety functions:	:	:	
Ensure SG Cooling Function	SG design	See Sub-chapter 5.4, section 4.2	
	Secondary Chemistry	<u>Corrosion product limitation through FAC mitigation:</u>	2.2.2
		pH, corrosion products sampling and monitoring	2.2.3 & 2.2.8
		<u>Mineral impurities mitigation:</u>	2.2.4
		<u>SGBD parameters monitoring, SGBD purification function, tightness technology of the condenser.</u>	2.2.6
	Choice of secondary side materials resistant to FAC	Choice of secondary materials resistant to FAC (chromium content in alloys for secondary system materials),	2.2.2
Transient optimisation	Lay-up specifications	2.2.7	
	Start-up: use of the ATD in order to limit impurities, feedwater oxygen limitation	2.2.5	
Ensure the Second Barrier Integrity to Limit the SGTR Risk	SG Design	<u>SG tube material</u> : Alloy 690TT resistant to corrosion	2.2.1
		<u>High permeability TSP</u> limiting the risk of blockage and pollutant hide-out	2.2.1
		Top of TS <u>corrosion limitation risk</u> due to the expansion process and tube to TS joint	2.2.1
	Secondary Chemistry	<u>Choice of reducing environment:</u> Oxygen and hydrazine monitoring in feedwater	2.2.3.2

Claim	Argument	Evidence	Section describing the claim
		<u>Pollutants mitigation:</u> Cationic conductivity, sodium, chlorides, sulphate, silica, suspended solid monitoring at APG [SGBS]	2.2.4
		<u>SGBD purification function and tightness technology of the condenser.</u>	2.2.6
		<u>Corrosion products limitation through FAC mitigation:</u> pH, choice of secondary materials resistant to FAC, chromium content, alloys for secondary system materials), corrosion products sampling and monitoring	2.2.2 & 2.2.3
		Transient optimisation	Start-up: use of the ATD in order to limit pollutants ingress
		Monitoring Hide-out return during shutdown	2.2.8
Limiting the impact on environment	Amine concentration optimisation	Amine concentration and nitrogen release limitation control	2.2.3.1
	Limiting solid waste	APG [SGBS] resin management	2.2.6
Sampling	RES and SIT design	Sampling locations	2.2.8
	Measurement frequencies	On-line control	2.2.8
		Periodic manual control	2.2.8
Unit availability	SG design	<u>SG tube material:</u> Alloy 690 resistant to corrosion	2.2.2
		<u>High permeability TSP</u> limiting the risk of blockage	2.2.2
		Top of TS <u>corrosion limitation risk</u> due to expansion process and tube to TS joint	2.2.2
		Provisions in the design to facilitate inspection and cleaning of affected areas	2.2.2
	Condenser Technology	Leak tightness technology of the condenser to limit the ingress of impurities	2.2.5
	Secondary Chemistry	pH <sub>T</sub> , impurities control	2.2.4
	Secondary System Materials resistant to FAC	Chromium content in secondary system materials	2.2.2

**Evidence Supporting the Claims linked with Secondary Chemistry**



### 2.2.1. UK EPR Steam Generator Design

The SG design supports the secondary barrier integrity [Ref-1]. The SG design has been optimised and performed through the selection of:

- The SG tube material;
- The TSP design and material;
- The Flow Distribution Baffle device;
- Manufacturing process to limit the risk of corrosion at the top of the tubesheet (TTS);
- Provisions in the design to facilitate inspection and cleaning of affected areas.

#### **Selection of Corrosion Resistant Materials:**

According to the main conclusions from corrosion tests, the following choices were made for the UK EPR SG design [Ref-1]:

- Alloy 690TT for the SG tube materials to limit the secondary corrosion risks such as Inter-Granular Attack and/or Stress Corrosion Cracking (IGA/SCC). Alloy 690TT has been extensively tested in the various concentrated chemical environments assumed to build up in secondary side superheated crevices of PWR steam generators by hideout of secondary water contaminants, and to be responsible for secondary side attack (IGA/SCC) of mill annealed Alloy 600 tubing. Alloy 690TT displays superior resistance compared to all other candidate steam generator tube alloys and is only vulnerable in very caustic environments, in the presence of lead (Pb) and possibly in environments contaminated with reduced sulphur species. Operating experience of Alloy 690TT tubing shows that no tubes have been damaged or plugged due to corrosion-related phenomena after up to 20 years in service. Only wear and fatigue have so far been responsible for the limited number of tubes that have been plugged in service.
- Stainless steel for the tube support plate (TSP) materials to protect them from generalised and FAC corrosion.

#### **EPR SGs Tube Support Plates Broaching:**

For the UK EPR, the SG was designed to maximise the heat exchange surface by installing as many tubes as possible in a given volume. To do so, a triangular pitch was considered, which induces the use of trefoil-shaped broaching. The trefoil-shaped broaching profile (well open to flow) of the UK EPR SG tube support plates is considered to have a high permeability since the thickness of the ligaments has been reduced in comparison with the quadrifoil-shaped profile, while maintaining sufficient mechanical resistance. Moreover, the brushing on both sides allows a smooth shape at the edge of the TSP which reduces the turbulent flows and potential deposit locations which brings some additional margins regarding risk of clogging compared to the previous 51B SG models. One of the main advantages of a high permeability TSP is to increase the recirculation ratio of the SG. Therefore, the water flow at the entrance of the tube bundle is increased. Since sludge deposit is correlated with low velocity area and boiling area, higher velocities on the top of the tubesheet are beneficial to the reduction of the sludge deposit on the tubesheet.

**Flow Distribution Baffle**

The flow distribution baffle is a device located between the TS and the first TSP. Its main objective is to force the fluid flow to penetrate deeply into the tube bundle thus reducing TS areas with low flow velocities. Until now, the experience feedback available on N4 SG units (first start-up 1996) from standard sludge lancing operations of the TS has shown that the amount of sludge deposit on the tube sheet is low. The average masses of dry extracted sludge have been less than 4 kg.

Moreover, the material grades retained for the secondary circuit components of the UK EPR present optimised chromium content in subjected parts of the feedwater system, which also limits the risk of FAC. Due to these improvements, the quantities of corrosion products which can enter the UK EPR SGs during normal operating conditions will be limited and the values observed on N4 SGs can be considered as an enveloping value for the UK EPR.

**Limitation of Corrosion Risk at the SG Top of TS**

The UK EPR SG is designed to reduce the risk of corrosion at the top of the TS. This is obtained through:

**Tube Expansion Process:**

UK EPR SG tubes are hydraulically expanded through the entire thickness of the tubesheet. This allows for the following:

- Excellent tube-to-tubesheet strength in addition to that provided by the tube-to-tubesheet weld;
- Elimination of the tube-to-tubesheet crevice to preclude concentration of harmful species and inter-granular attack;
- Preclusion of primary side stress corrosion cracking because of the limited level of residual stresses;
- Preclusion of secondary side stress corrosion cracking because of low level of residual stresses.

**Tube-to-Tubesheet Joint**

With regard to N4 SGs, recent optimisation of the tubesheet drilling process and better control of drilling the external diameter reduces the maximum gap between tubesheet bore and outer wall of the tube in the UK EPR SG.

This measure contributes to limiting residual stress levels in the transition zone after tube expansion. This improvement increases the margin concerning the risk of corrosion in that region. Furthermore, this has already been implemented on many replacement steam generators in France and abroad.

This improvement has to lead to the following conclusions:

- For the tube secondary side / outer skin:
  - At such low levels of residual stress and at nominal secondary chemistry conditions, corrosion can be considered negligible at the SG TTS.

- For the tube primary side / inner skin:
  - Risk of corrosion with the primary coolant is low and such levels of residual stresses are considered acceptable. This is ensured by the Operating Experience on existing plants that show no indication of primary side corrosion on SGs or replacement SGs equipped with the tube bundle made of Alloy 690TT since commissioning.

#### **Provisions in the Design to Facilitate Inspection and Cleaning of the Potentially Affected Areas**

The UK EPR steam generator secondary side is equipped with access openings that facilitate inspection and cleaning. Eight hand holes are located at the level of the flow distribution baffle. They are mainly used for examination of the lower tube bundle, as well as for tubesheet cleaning and lancing operations. Two inspection ports or eyeholes are located at the level of Tube Support Plate (TSP) No. 6. They are mainly used for examination of the upper tube bundle region.

The cleanliness of the secondary side of the steam generator is critical to the good performance of the steam generator. Therefore, several aspects have been considered to ensure that the secondary side can be adequately inspected and cleaned, if necessary.

- **Tubesheet Examination**

Although the SG is designed to minimise the sludge deposited on the TTS, an accumulation of sludge in this area, due to external pollution, may occur. The TS should be examined periodically by means of suitable inspections to verify its cleanliness.

The hand holes located above the TS levels allow for the assessment of the cleanliness of the TS.

- **Tubesheet cleaning**

Sludge lancing is a cleaning process used to remove the sludge from the top of the tubesheet by using high pressure water jets to sweep the surface (demineralised water under pressure). The SG is designed to allow for such cleaning operations.

The main benefits of sludge lancing are to preclude concentration of harmful species due to alternate wetting and boiling, to reduce the secondary side sludge inventory, and to preclude build-up of hard sludge collars such that long term integrity of the tubing is maintained and achieved.

The UK EPR SG allows sludge lancing through the hand holes located at the level of the flow distribution baffle.

Another method of secondary cleaning is chemical cleaning. The SG pressure retaining vessel is designed with a dedicated corrosion allowance for chemical cleaning during the life of the SG. Note that the quantity and frequency of chemical cleaning varies since it is dependant on the process and chemicals utilised.

### 2.2.2. Secondary System Material Choice for the UK EPR

FAC causes wall thinning on the inside surface of components and can lead to leaks or ruptures if wear is not detected in time. Parameters playing a role on FAC are [Ref-1]:

- Flow rate and velocity;
- Geometry of the flow path;
- Temperature;
- Chemistry (pH<sub>T</sub>, reducing agent, oxygen concentration);
- Chemical composition of the steel (chromium content); and
- Steam quality (hygrometry, temperature, silica content).

In the context of PWR operations, there may be several types of material which are exposed to a wide range of temperatures, corrosive media and moving liquids. Virtually anything that is exposed to a moving liquid can be subjected to FAC.

FAC of carbon steels has been responsible for the degradation of the steam and water circuits of fossil and nuclear power plants. It is consequently of primary importance in the design and operation of the secondary coolant system of PWRs. Consideration should be given to the wide temperature range associated with the system (ranging from 35°C in the condenser to 293°C in the steam generator) and the presence of both steam and liquid phases. Besides these objectives, the chemical treatment should be chosen to avoid reagent concentrations in the crevices areas of SGs. For this reason, the system requires the use of all volatile treatment (in water and steam part) in order to maintain pH control throughout the circuit.

For the UK EPR, the turbine hall components are designed for a 60-year life span if they cannot be easily replaced. These include not only the piping but also all components (reheaters, etc.) and the lagging support components. The effects of FAC have been taken into account in the basic design of all the piping in the turbine hall that is sensitive to the FAC process.

#### 2.2.2.1. Status of FAC assessment

FAC has been considered in the design of the UK EPR for both pipes and components. Susceptible areas have been identified and the following preventive measures will be implemented:

- Control of secondary circuit chemistry;
- Selection of appropriate pipe material according to sensitivity to FAC;
- Selection of appropriate welding material for the installation of piping on site;
- Additional pipe thickness will be allowed in susceptible areas and components to counterbalance wear caused by FAC over a 60-year life span.

The chromium content control is the main reliable solution to prevent the occurrence of FAC in steel piping. The following considerations have been retained for the UK EPR:

- Pipes

Specific alloys have been chosen with sufficient chromium content to mitigate, or even to eliminate FAC degradation in the UK EPR.

The welding material is the same as the pipe material and includes sufficient chromium content for all the sensitive pipes. Therefore, the risk of FAC associated with low chromium content in the welding material, is eliminated.

For equipment such as the High Pressure (HP) feedwater heaters or Moisture Separator Reheater (MSR) the same considerations have been taken into account leading to the choice of either a low alloy steel (with sufficient chromium content) or stainless steel.

The Operational Experience Feedback related to FAC has been integrated in the UK EPR plant series specifications. The main new requirement for the UK EPR, compared to the previous N4 plant series, is the use of low alloy steel with high Cr content.

### **2.2.3. Secondary Chemistry Conditioning of the UK EPR**

The main objectives of the secondary chemistry conditioning are to avoid the following [Ref-1]:

- FAC in the secondary side systems, especially in the steam systems with two-phase flow;
- general corrosion in secondary side systems;
- heat transfer degradation problems.

The pH plays an important role on the generalised corrosion and the FAC of carbon steel and/or low alloy steel of secondary circuit [Ref-1]. To mitigate as much as possible FAC in the secondary systems and the transport of corrosion products in the SGs, an optimal pH value has to be defined. The secondary water chemistry also plays a role in the phenomena of fouling or clogging of the SG. The optimal pH value must take into account these phenomena.

The risks of corrosion (type IGA/SCC) of SG tubes are especially linked to the presence of impurities which can concentrate in SG confined areas. With an absence of pollution, the secondary water pH has a low impact on these types of corrosion.

#### **2.2.3.1. Optimal pH Value**

The challenge in defining an optimal pH for the secondary water is due to different considerations. Firstly, the diversity of secondary circuit materials could result in variable performance with regard to the corrosion phenomena. Secondly, the diversity of environments can be mono or biphasic. This is further compounded due to the operating temperature varying between 35°C at the condensate extraction and 293°C at the APG [SGBS].

Regarding safety, optimal pH is defined to mitigate generalised corrosion and FAC of carbon steel and/or low alloy steel of secondary circuit materials. Indeed mitigation of corrosion product ingress into the SG reduces the phenomena of SG fouling and thus the risk of TSP clogging.

Determination of a pH range for the UK EPR must take into account the design choices of the secondary system:

- No copper alloy (allowing high  $\text{pH}_{25^\circ\text{C}}$  values);
- Use of FAC resisting materials in erosion-corrosion sensitive areas;
- No condensate polishing at power (continuous condensate polishing involves running at a limited pH);
- No APG [SGBS] resin regeneration (to avoid impurity ingress into the secondary circuit).

#### pH Impact on the Generalised Corrosion of Carbon Steels [Ref-1]

The most sensitive materials to generalised corrosion are carbon steels and low alloy steels. Generalised corrosion leads to the formation of oxides. Oxides are more or less protective depending on their nature. At secondary side operating temperatures (from  $35^\circ\text{C}$  to  $293^\circ\text{C}$ ), generalised corrosion of carbon steels leads to the formation of magnetite ( $\text{Fe}_3\text{O}_4$ ) in a reducing medium; whereas, in oxidising conditions the oxide formed is hematite ( $\text{Fe}_2\text{O}_3$ ). The formation of this oxide layer ensures the passivation of the surface and thus the decrease of the corrosion rate.

Corrosion rate is correlated with the solubility of the oxide layer, which varies with the pH value. At a high temperature, without oxygen, the minimal corrosion rate is obtained when the  $\text{pH}_{25^\circ\text{C}} \geq 9$ .

#### pH Impact on FAC [Ref-1]

Erosion-corrosion is a particular phenomenon of generalised corrosion. Observed corrosion rates are increased by the fluid flow. This type of corrosion is called FAC. FAC is a process whereby the normally protective oxide layer on carbon steel or on low-alloy steel dissolves into a stream of flowing water or a water steam mixture. FAC does not occur in pipes carrying dry or superheated steam.

The effect of FAC has to be considered with regard to pipe thickness loss and to corrosion product transport in the SG.

Three main types of conditioning regimes have been considered in detail for the UK EPR taking into account the amount of nitrogen liquid waste release and the APG [SGBS] resin lifetime: Ethanolamine (ETA), Morpholine / ammonia and ETA / ammonia.

Two types of calculations have been performed with the BRT-CICERO model on secondary system piping for evaluating and understanding FAC:

- The first calculation was performed for the principal secondary circuit at  $\text{pH}_{25^\circ\text{C}}$  of 9.2 (ammonia conditioning which is a bounding conditioning) for the feedwater system piping (SG feedwater line) at  $230^\circ\text{C}$  and with a material chromium content of 0.15%. The aim of this calculation was to identify sensible areas where additional thickness may be required. These calculations showed that the FAC kinetics can be reduced by a factor 2 when utilising a  $\text{pH}_{25^\circ\text{C}}$  of 9.5 compared to 9.2. Moreover, with this conditioning (ammonia  $\text{pH}_{25^\circ\text{C}}$  of 9.2) and material chromium content of 0.15% the guarantee of a 60-year lifespan is obtained with the inclusion of additional thickness in specific areas.

- The second calculation was performed for the conventional circuit piping. The approach was to perform modelling of FAC kinetics on three lines of a N4 unit (N4 design is very close to the EPR design), which were chosen for their bounding characteristics (temperature of 180°C, pipe geometry, high flow velocity). The modelling considered different chemical conditionings in order to determine the minimum chromium content of the alloy, which would guarantee a 60-year lifespan. In the presence of a chemical conditioning with ammonia at a  $\text{pH}_{25^\circ\text{C}}$  of 9.5, these studies concluded that chromium content higher than 0.25% would be necessary, along with an additional thickness. Moreover, it was discovered that a  $\text{pH}_{25^\circ\text{C}}$  of 9.8 with ammonia allows limiting the corrosion kinetics by a factor of 2 compared to a  $\text{pH}_{25^\circ\text{C}}$  of 9.5.

The results of the calculations lead to the retention of a  $\text{pH}_{25^\circ\text{C}}$  of 9.8 with ammonia as a minimum target pH value for the definition of the UK EPR chemical conditioning. As the FAC rate is a function of temperature and steam quality, pH calculations have been performed in order to determine which amines are considered the equivalent optimal pH at high temperature. Those calculations taking into account the alkalinity and volatility of the amines considered (morpholine, ETA, and ammonia) lead to a minimum  $\text{pH}_{25^\circ\text{C}}$  of 9.4 for the UK EPR, as a preliminary value. This  $\text{pH}_{25^\circ\text{C}}$  will be obtained with appropriate amine concentrations. Monitoring of the SG  $\text{pH}_{25^\circ\text{C}}$ , which is directly linked to the feedwater pH value, is performed with an expected value higher than 9.2.

#### pH Impact on Fouling and Clogging of SGs [Ref-1]

The fouling of SGs results in an accumulation at the tube bundle surface of corrosion products formed in the whole of the secondary circuit. With time, this deposit grows, solidifies, and forms a layer thermally resistant on the wall of tubes, thus decreasing the thermal efficiency of the SG.

The exact causes of clogging of the TSP broached openings observed in several plants are not exactly known yet and are still subject to on-going investigations. It has been speculated that the clogging process is based on iron precipitation at the broached locations of the TSP and/or the sticking of magnetite particles. These processes require iron ingress in the SG, essentially in the form of iron oxide.

To limit this phenomenon an optimisation of the pH value is required. There are some correlations between secondary water chemistry and fouling or clogging of SGs which have been identified by international feedback.

French units operating with morpholine at  $\text{pH}_{25^\circ\text{C}} = 9.2$  show higher pressure drops in the SG secondary side compared to the ones operating with morpholine  $\text{pH}_{25^\circ\text{C}} = 9.6$  or ammonia  $\text{pH}_{25^\circ\text{C}} = 9.7$ . In France, among the 22 plants operating at low pH, 10 of them presented significant clogging in 2006. Further experience analysis shows that the low pH value is a contributing factor to TSP clogging and/or SG tube fouling.

The same conclusion can be deduced from Japanese experience where clogging problems have been observed on plants with a low  $\text{pH}_{25^\circ\text{C}}$  ( $\text{pH}_{25^\circ\text{C}} = 9.2$ ). Higher clogging rates have also been reported on U.S. plants with low  $\text{pH}_{25^\circ\text{C}}$  ( $\text{pH}_{25^\circ\text{C}} < 9.3$ ).

Moreover, the material grades retained for the secondary circuit components of the UK EPR present optimised chromium content, also limiting the risk of FAC. The choice of material linked with  $\text{pH}_{25^\circ\text{C}}$  optimisation will limit the risk of fouling or clogging in the UK EPR.

### 2.2.3.2. Optimal Hydrazine Concentration [Ref-1]

Hydrazine is added to the secondary system in PWR plants to minimise material corrosion by limiting the oxygen content, maintaining a reducing potential, and developing a protective film on the metal (magnetite). With pH, electrochemical potential is one of the important parameters for limiting local corrosion such as IGA/SCC. Therefore, the addition of hydrazine into the secondary system:

- Reduces oxidising agents such as oxygen;
- Reduces oxidising ability of sludge due to hematite;
- Reduces the redox potential in the environment.

As a reducing agent, hydrazine can reduce ferric oxide to magnetite (the thermo-dynamic stable phase of iron oxide in reducing conditions) and then produces a protective film. The presence of iron III (such as haematite, ferric oxide, etc.), transported by the feedwater into the SG, is considered harmful because of the oxidising ability brought to the chemical environment and sludge.

One of the major drawbacks in using hydrazine is its instability at high temperature. Most hydrazine, which does not react with oxygen, thermally decomposes to form ammonia. This decomposition is very fast at high temperature ( $T > 200^{\circ}\text{C}$ ), and contributes to an increase in pH.

#### Hydrazine Effect on IGA/SCC

The major cause of corrosion in the SGs is localised corrosion which depends on many factors such as temperature, chemistry, and impurities in confined areas. The electrochemical potential and the pH are two important parameters regarding localised corrosion such as IGA/SCC. Oxidising conditions can increase the risk of IGA/SCC, while reducing agents, such as hydrazine, prevent IGA/SCC by modifying the corrosion potential of metal.

Alloy 690TT is the least sensitive regarding IGA/SCC. However, it is important to optimise the hydrazine concentration to limit the risks of corrosion because the chemistry in the confined area of the SGs is difficult to control. Operational experiences support the lower limit of 50  $\mu\text{g}/\text{kg}$  as this value can usually be achieved and ensured a satisfying reducing media.

However, in presence of oxygen, hydrazine concentration can be above this limit and in this case, it is necessary to maintain a mass ratio  $(\text{N}_2\text{H}_4)_{\text{feedwater}}/(\text{O}_2)_{\text{condensate}}$  between 5 and 10.

#### Hydrazine Impact on FAC Kinetics

The hydrazine effect on FAC is second-rate compared to the effects of other parameters; such as temperature or pH.

#### Recommended Hydrazine Concentration for the UK EPR Reactor [Ref-1]

The optimisation of hydrazine concentration should consider the drawbacks of a high concentration, mainly the environmental impact and the operation of SGBD resins (stability, lifetime, etc.). Based on these considerations the hydrazine concentration range recommended for UK EPR reactor during normal operation is between 50 and 100  $\mu\text{g}/\text{kg}$ .



Additionally, during transient conditions, and in the presence of oxygen, the hydrazine concentration may be greater, providing that a mass ratio of  $(N_2H_4)_{\text{feedwater}} / (O_2)_{\text{condensate}} > 5$  to 10 is maintained.

#### **2.2.4. Secondary System Impurity Limitation for the UK EPR**

Experience feedback indicates that the SG secondary side is sensitive to localised corrosion due to the presence of chemical impurities. The corrosion products and chemical impurities in feedwater tend to concentrate in the SG and can cause corrosion of SG tubes (IGA/SCC) [Ref-1].

The objectives of secondary conditioning optimisation detailed previously are to limit the corrosion phenomena of the secondary system materials, SG included, and thus to limit corrosion product transport and deposition [Ref-1].

Although the SG design is optimised (see section 2.2.2) and the SG chosen tube materials (Alloy 690) are less sensitive than Alloy 600 materials to the corrosion phenomena in normal power operating conditions, it is nevertheless essential to limit the impurities in the secondary coolant such that the risks of local corrosion in the secondary circuit and more precisely in the SG are limited.

##### Impurities to Limit in the Secondary System

Five classes of chemical impurities are generally considered responsible for corrosion of SG tubes in confined areas:

- Highly concentrated caustic media;
- Sulphate species which could come from resin thermal decomposition;
- Reaction products from the sulphate species in a reducing environment;
- Highly concentrated salty solutions, coming from condenser leakages;
- Presence of lead.

To prevent IGA/SCC, the following impurities are limited in the SGs:

- Sodium (to avoid caustic pollution);
- Chlorides;
- Sulphates (and associated species like sulphides and thiosulphates).

##### Lead

Although lead contamination is a known corrosion factor, the available operating data is insufficient to define acceptable concentrations in feedwater and at the APG [SGBS]. For the UK EPR, no secondary material contains lead in normal operation. Nevertheless, lead concentration has to be measured in the sludge, to confirm the absence of the pollutant.

#### Sodium and Cation Conductivity [Ref-1]

It is important to consider the effects of sodium and cationic conductivity. Sodium is an alkaline cation which can concentrate. This is one of the main causes of caustic corrosion, particularly in the SGs. The most frequent types of corrosion due to sodium are IGA/SCC. As such, sodium content is limited in the SG blowdown.

The cationic conductivity at 25°C in the SG secondary sampling system (RES) is an indirect measurement of the total amount of dissolved salts and an indirect way of monitoring saline impurities in the SGs. An increase in the cationic conductivity can be attributed either to an increase of strong anions (sulphates, chlorides), and/or organic impurities (mainly acetate, formate) as well as dissolved CO<sub>2</sub>. In cases of elevated cationic conductivity, additional impurity measurements such as chlorides and sulphates or organic concentration measurements are required to establish the source of the pollution.

Sodium monitoring provides, with cationic conductivity, a very sensitive way to detect any ingress of impurities into the secondary system.

Taking into account the corrosion resistance of Alloy 690TT in a caustic environment, the limiting value for sodium in the SG during normal operation is 20 µg/kg. Regarding the cationic conductivity the maximum value of 1 µS/cm, corresponding to normal practice, is retained.

#### Chlorides and Sulphates [Ref-1]

Additionally, it is important to control chlorides and sulphates in the secondary system. Chlorides have a detrimental effect on the SG tube bundle. They can cause pitting corrosion on tubes when oxygen is present, tube denting when magnesium salts are present (seaside units), and acid corrosion in confined areas of low alloy steel.

Sulphur compounds are undesirable because they can create reduced compounds that can damage SG tubes (IGA/SCC). Sulphur is not directly controlled in the secondary system because sulphate ions are easier to detect. Sulphates are controlled to survey the risk of reduced species ingress into the steam generators. It is known that sulphates may be reduced in reduced sulphur forms due to the presence of hydrazine.

Chlorides and sulphates are controlled through the monitoring of the cationic conductivity. The limiting values are consistent with low chloride or sulphate concentrations. Only expected values are specified at the SG blowdown for those species, with a normal operating value of less than 10 µg/kg.

Measurements of chlorides and sulphates in SG blowdown must be performed periodically if there is no change in cationic conductivity or after exceeding an expected value for cationic conductivity.

#### Silica Control

Silica is an element normally controlled and subjected to limits in the SG water. Silica combined with mineral impurities, creates diverse slightly soluble compounds that can deposit on the turbine blades. Moreover, aluminosilicates are known to form hard sludge in SGs. This element is only an indicator that is specified as an expected value and with a normal operating value of 1 mg/kg at the SG blowdown.

### Suspended Solids and Iron Control

Suspended solids in the secondary system mainly come from secondary system corrosion products, i.e., iron oxides. Associated measurements of suspended solids at the SG blowdown and iron in the feedwater allow determination of the effectiveness of the blowdown system, and is an indicator of SG fouling.

The recommendation for the UK EPR is to regularly measure the feedwater iron concentration to predict SG fouling and to schedule outage activities such as sludge lancing and chemical cleaning more rationally.

### **2.2.5. Secondary System Pollution Ingress Limitation**

The UK EPR chosen solution for limitation of secondary pollution ingress is based on the following coherent technological approaches:

- Tight and reliable condenser (titanium tubes + titanium plated tube support plates with rolled and welded tubes [Ref-1]);
- Quick detection of pollution at convenient locations by the feedwater chemical sampling system (SIT);
- Purification of steam generator blow down system to 1% feedwater flow (see section 2.2.6);
- ATD System (Start-up Condensate and Feedwater Purification System) at plant start-up.

During outages, the ATD removes impurities (corrosion product and ionic impurities) accumulated in the condensate-feedwater cycle through specifications on impurities and prevents start-up delays (see section 2.2.7).

During operation, the measurements of secondary chemical parameters performed through the Turbine Hall Chemical Sampling System (SIT) allow an early detection of potential cooling water ingress. Moreover, the high pH conditioning by amine of the secondary system prevents the risk of corrosion products in the feedwater and condensate plant.

In addition to the above features, the ADG deaeration tank avoids the presence of oxygen in feedwater in order to limit the occurrence of corrosion products. The remaining dissolved oxygen is consumed by injection of hydrazine in the secondary circuit with the Chemical Reagent Injection System (SIR system).

### **2.2.6. APG [SGBS] Purification**

The APG [SGBS] maintains the good quality of the SG water as required by the chemical specification (see section 3). A number of design choices have been made (see PCSR Sub-chapter 10.4, section 7) with respect to the APG [SGBS] demineralisers for the UK EPR:

- SG blowdown design flow rate of 1% of full load of steam flow;
- Two parallel demineralising trains of 50% capacity each;
- Each demineralising train will consist of a cation exchanger (cationic resin) followed by an anion exchanger (anionic resin);

- The system is non-regenerable and resins will be disposed of after exhaustion [Ref-1];
- There will be the same volume of resins in the cation and anion beds.

The design of the APG [SGBS] for the UK EPR has taken account of operational experience of APG [SGBS] demineraliser systems across the existing EDF fleet of reactors [Ref-1], which is based on the use of cationic followed by anionic resin beds, and operation of cationic resin in amine form.

The APG [SGBS] resins in the existing fleet of reactors are used past the amine breakthrough (contrary to most of other PWRs with regenerable resins), so that mixed resin beds are no longer necessary as a final polishing treatment and can thus be replaced by an anionic resin. An additional control on sodium concentration is performed downstream of the demineraliser beds, to control effectiveness of cationic species retention.

The use of separate cationic and anionic beds enables specific replacement of either one or the other of the ionic forms when it is saturated. If an arrangement of a cation bed followed by a mixed bed were to be used then replacement of the mixed bed would take place when there is breakthrough by either cationic or anionic species. On this basis, replacement would be necessary even though either one of the anionic or cationic resins present in the mixed bed was not fully saturated. Accordingly, the use of separate cationic and anionic resin beds will minimise the frequency of resin replacements.

The proposed arrangement for the APG [SGBS] demineraliser system for the UK EPR is based on the assumption that resin will not be regenerated once it is spent, but replaced as practiced across the existing fleet of reactors. This is contrary to the operation of many PWR APG [SGBS] demineraliser systems which are based on the use of regenerable cation beds and mixed bed polishers.

When considering the cationic resin, the key factor determining its lifetime is the reagent used to achieve an alkaline pH. The cation in the reagent will displace the hydrogen ions ( $H^+$ ) present in the hydrogen form of the cationic resin when it is first brought into use. The reagent will affect the properties of the resin with respect to the retention of cationic impurities such as sodium.

Cationic resin affinities (for the resins planned to be used in the UK EPR) for the main cations present in the secondary circuit can be ranked as [Ref-1]:



Specifications require that cation beds be replaced on the basis of sodium breakthrough. The typical concentration of sodium ions ( $Na^+$ ) in the APG [SGBS] is 0.5 – 2.0  $\mu g/kg$ , based on operational experience of the French fleet. Operational practice has been to replace the APG [SGBS] cationic resin before the sodium ion concentration exceeds 2.0  $\mu g/kg$  downstream of the demineraliser beds. This is the main factor that determines the lifetime of cationic APG [SGBS] demineralisers.

As noted above, resins are supplied in hydrogen form, i.e., the cation initially present in the resin is the hydrogen ion. There are two main phases which contribute to the overall lifetime of the cationic ion exchange resin:

- The time taken to saturate the resin with amine (i.e., replacement of the hydrogen ions with amine ions);

- The time period prior to reaching a sodium ion concentration of 2.0 µg/kg in the water downstream of the demineraliser.

Demineraliser bed lifetime is only one of a number of factors which need to be taken into account in making decisions about the management of the APG [SGBS] and the protection of the secondary circuit from corrosion. An appropriate balance has to be struck between the conditioning regime, the need to minimise impurities in the secondary circuit, the amount of reagents required to achieve the required pH and waste arising (in both spent resins and nitrogen compounds in liquid discharges) from the APG [SGBS].

### 2.2.7. Transient Optimisation

The start-up phase should be used to reduce impurity levels in the secondary circuit and the SGs, in particular the oxidising species. Before reaching the operating temperature, it is important to maintain a sufficient blowdown flow rate to remove contaminants and meet operating chemistry specifications.

#### Start-up phase

Oxygen concentration has to be controlled during the start-up phase. In order to minimise the generalised corrosion of carbon steels and the risks of pitting corrosion in the SG, the oxygen concentration in feedwater has to be less than 100 µg/kg for temperatures higher than 120°C [Ref-1].

During start-up, conditioning would minimise all corrosion phenomena, as observed during power operation. To control oxygen ingress during the start-up process, hydrazine is added, especially prior to criticality when the condenser air tightness can not be fully achieved. A hydrazine concentration > 100 µg/kg is recommended in the APG [SGBS] to ensure that oxygen control and reducing conditions in the SGs are maintained.

Following plant shutdown, SGs contain more impurities and oxidising species than during normal operation, thus the start-up phase has to be used to remove them by operating with a maximum blowdown flow rate in order to reach the normal operating impurity concentrations.

Due to the use of the Start-up Condensate and Feedwater Purification System (ATD) a chemical purification will be obtained during start-up. The ATD [Ref-2] has been designed to ensure chemical purification and heat treatment functions of the water/steam system in the turbine hall during the start-up phase [Ref-1] [Ref-2]. The specific requirements for the ATD are as follows:

- To obtain chemical and thermal properties of the secondary system in the proposed start-up schedule;
- To help start-up after dry lay-up of the feedwater plant (hot draining and hot air sweeping);
- To treat a volume of 1,750 m<sup>3</sup> (with a chemical treatment flow rate of 300 m<sup>3</sup>/h).

The ATD is located at the condensate pump letdown (limit of pressure with membrane).

This system aims to purify the contents of the condensate and feedwater plant in the unit start-up phase, to enable SG feedwater to be switched over to water that has the best possible chemical properties.

The ATD prevents impurities entering the SG during start-up and thus limits the potential impact on corrosion and fouling.

During the start-up phase cationic conductivity, sodium and oxygen concentrations are specified and maintained in the feedwater coming from the ATD.

#### SG Lay-up [Ref-1]

The SG lay-up specification during shutdown is determined in order to keep the SG in a clean state and allow start-up in good conditions. Two types of SG lay-up are currently used, depending on the operations that will be performed during the outage:

- Dry lay-up;
- Wet lay-up.

#### **Dry Lay-up**

Concerning dry lay-up, a maximum relative humidity percentage is required. The objective is to limit the condensation in the SG and reduce harmful species such as chlorides (seaside unit), contained in the air. The maximum relative humidity is 40% for the coldest point of the SG.

#### **Wet Lay up**

The wet lay-up of the steam generator, with chemically treated water, during outages is necessary to minimise corrosion and oxidation during the lay-up period itself and also corrosion during subsequent start-ups and power operations. Protection is provided by an amine for pH control and by hydrazine to maintain a protective oxide film and a reducing environment.

There are several wet lay-up treatments available depending on the expected length of the outage. When the time period of cold shutdown is less than one week and if no operation in the steam generator is planned, the recommendation is not to drain the SG. In this case, SGs are subjected to wet lay-up using operation medium of the previous cycle. The specifications for this operation are the same as the specifications for normal power operation. When the expected length of the outage is higher than 7 days (between 7 days and 1 month) an air blanket will be used.

The preliminary recommendations for SG wet lay-up are a hydrazine concentration higher than 75 mg/kg associated with a  $\text{pH}_{25^\circ\text{C}} > 9.8$  to minimise corrosion of carbon steels. Depending on the time period of the wet lay-up, an additional hydrazine concentration of 8 mg/kg should be added per day.

#### Hot shutdown phase

During this phase the recommendation is to maintain the SG medium at a ratio of hydrazine/oxygen = 5 to 8, associated with hydrazine concentration between 50 and 100  $\mu\text{g}/\text{kg}$ , as in normal power operation.

During hot shutdown corrosion risks are less important than during normal power operation due to the low thermal flux between primary and secondary coolant. However, impurities have to be limited in order to have optimal conditions for the normal operating condition. The hot shutdown chemical specification is focused on oxygen concentration limitation in the SG feedwater and cationic conductivity in the SG.

The diminution of thermal exchange between secondary and primary circuit can lead, during the transients (hot shutdown and cooldown to cold shutdown), to the hide-out return of some species which have been held at the intersections between tube and tube support plate and at the tubesheet. This phenomenon can be measured by the augmentation of sodium and cationic conductivity at the APG [SGBS] sampling.

This phenomenon is taken into account in the specification by allowing higher expected values at the APG [SGBS]: the criteria for the expected values of sodium, chlorides and sulphates are lower than 100 µg/kg, and lower than 2 µS/cm for the cation conductivity with a maximum value of 10 µS/cm. Accordingly, it is recommended that monitoring the hide-out return phenomenon during shutdown is preferred.

The hide-out return results enable estimation of the amount of pollutants which have concentrated in SG crevices during the previous cycle, and the local pH at temperature in SG crevices.

### 2.2.8. Optimal Sampling

Two systems ensure the secondary chemistry sampling and monitoring:

- Steam Generator Secondary Sampling System (RES) for the sampling of lines from the secondary side of the SG and purification of SG blowdown;
- Turbine Hall Chemical Sampling System (SIT) for the secondary coolant quality of the turbine hall.

#### Steam Generator Secondary Sampling System (RES)

The RES (as the REN [NSS]) contributes to two of the main safety functions:

- The RES contributes to the containment of radioactive substances through the containment isolation function. Additionally, the RES provides liquid samples to the Plant Radiation Monitoring System, for monitoring Steam Generator integrity.
- By sampling and analysing samples taken from the nuclear circuits, the RES supports the maintenance of the chemical and radiochemical characteristics of the fluids coming from the secondary part of the SG, between specified limit values allowing plant operation.

The main parameters which are continuously monitored are:

- Cation conductivity;
- Sodium;
- SG sample activity through the Plant Radiation Monitoring System (gamma activity monitoring - this measurement is complementary to the N-16 monitoring by the main steam line of the secondary circuit due to the installation of N-16 detectors in order to detect potential primary to secondary leaks).

The RES grouped sampling of the secondary section of the SGs and SG blowdown purification unit is carried out on the bench as, most of the time, the sampled fluids are considered to be inactive or occasionally present low activity. The RES sampling lines which can be monitored online, are permanently in service (except during maintenance), in order to obtain representative samples rapidly by continuous circulation of the fluid. The samples are therefore recycled, in order to limit the discharges, except in the case of chemical pollution.

The design of the RES allows for the following: the centralised and local sampling and analysis of liquid samples, the monitoring of chemical and radiochemical characteristics, the limitation of radiation exposure to personnel and the environment (ALARP), the sample recycling to minimise waste, minimisation of high energy pipe length outside the containment, and the minimisation of delay time to get representative samples.

The RES samples taken on high-energy fluids are cooled down and then the pressure is reduced. One of the UK EPR RES main developments is that flow on each line can be regulated independently of the pressure set point. The fluids are then heat treated, so that the samples and/or measurements can be made in representative conditions with no risk to the operators. The line-ups that enable the various samples to be taken are obtained by remote electrical control through a specific man-machine interface.

The quality and process measurements of the RES are continuously monitored. In case one or several of these measurements deviate from their normal operating range, automatic signals are created, automatic corrective measures are initiated, or signals are created to initiate manual measures.

Grab sampling can be considered as a functional redundancy for the online chemical parameters. If these corrective measures are not successful, protective orders are performed if applicable.

The control loops of the RES main sampling lines are:

- Supply of minimum and maximum thresholds in various parts of the RES so as to check that temperature, pressure and flow rates are compatible with the functioning of the devices and analysers.
- Regulation of the pressure reducing valves of the sampling lines, so as to ensure a constant downstream pressure. Whereas the backpressure valves at the end of the sampling lines ensure a sufficient and constant flow rate in the sampling lines.
- Start-up procedures for slow increase of flow rate are to mitigate thermal shocks. These could occur at RES start-up or at restarts of the RES after sampling had been interrupted because the heat exchangers shell side is still circulated by cooling water of the RRI [CCWS]. Motorised flow control valves are installed in order to efficiently protect heat exchangers from thermal shock by a slow increase of sample flow rates. These valves close quickly when sampling lines are put out of service.
- The re-injection of the RES secondary samples and of the REN [NSS] primary samples is controlled by a level control in the respective back feed vessel.

During operation, the measurements of secondary chemical parameters performed through the Feedwater Chemical Sampling System (SIT) allow early detection of potential cooling water ingress.



Turbine Hall Chemical Sampling System (SIT)

The main improvements made to the UK EPR Turbine Hall Chemical Sampling System (SIT) are listed below [Ref-1]:

- Doubling up of the overall CEX conductivity measurement. This provision enables prompt action to be taken against cooling water ingress.
- On-line measurement of sodium on the CEX (this provision for a coastal plant confirms the diagnostic of cooling water ingress, but also detects SER makeup water pollution).
- pH measurement on CEX.
- Installation of magnetic protection filters (designed to retain magnetite transported in the sampling line) installed upstream of the mechanical filter of Johnson mesh type (3  $\mu\text{m}$ ), itself placed upstream of the on-line analysers, so as to prevent their fouling by suspended solids.
- Implementation of a local discontinuous sampling system with integration of the filter of the AHP header for total iron measurement (source of corrosion products which may result in clogging of the steam generators).

The main centralised sampling lines of the SIT are:

- For CEX condensate: local  $\lambda^+$  measurement under each spur of the condenser tube bundle, local on-line measurement of  $\lambda^+$  and centralised on-line measurement, pH, Na,  $\text{O}_2$  at the common discharge sampling of the extraction pumps on the common extraction manifold.
- For AHP centralised on-line measurement: pH,  $\text{O}_2$ ,  $\text{N}_2\text{H}_4$  and  $\lambda^+$ .
- For GSS (moisture separator-re-heaters system): centralised on-line measurement:  $\lambda^+$ .
- For VVP [MSSS] Main Steam System: centralised measurement:  $\lambda^+$ .

### 2.3. IDENTIFICATION AND CLASSIFICATION OF SECONDARY CHEMICAL PARAMETERS

The classification of chemical parameters can be performed from the below listed criteria:

- As a function of the applicability of the parameters:
  - Control parameters having a direct link with the mitigation and control of the consequence on safety, radiation fields, environment, aggression, maintenance and operation issues. These parameters are associated with a limit value of which violation implies a procedure to apply.
  - Complementary parameters which assist chemistry staff in interpreting variations in the system chemistry.

This final classification will be defined in the applicable operating procedures.

- As a function of the domain:
  - safety and material integrity;
  - environment;
  - plant availability.
- Based on the elements provided in the previous paragraphs, the values associated with each parameter are the result of several compromises between the risks and the benefits associated with the different parameters during the different conditions of operation. The table in section 3 provides some **preliminary values** for parameters. The justification of the values is provided taking into account the balance between the positive and negative effects according to NPP feedback, test laboratories and/or modelling evaluations.
- The numerical values will be defined by the operator in the operating procedure of the UK EPR.

The table below provides the synthesis of influent parameters in the secondary circuit where each parameter is reported as function of its classification and domain.

		<b>Control Parameter</b>	<b>Complementary Monitoring Parameters</b>
Domain	Safety	Nitrogen-16 and Activity KRT [PRMS] – Plant Radiation Monitoring System)	
	Material Integrity	pH <sub>25°C</sub> FW Oxygen concentration in CEX SG Sodium concentration SG Cation Conductivity	FW Iron concentration FW conductivity SG pH <sub>25°C</sub> SG Chlorides, sulphates, silica concentrations SG Suspended Solid
	Environment	pH <sub>25°C</sub> FW	
	Operational Availability		FW Iron concentration SG Suspended Solid

**Secondary Chemistry Parameters Monitoring during Normal Power Operation**

**3. PRIMARY AND SECONDARY CHEMICAL AND  
RADIOCHEMICAL PARAMETERS – PRELIMINARY VALUES**

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b

For the complementary parameters which will assist the chemistry staff in interpreting variations in the system chemistry, the expected values will be defined in operating procedures. These parameters are as follows:

- B-10 enrichment (at. %);

- Calcium, aluminium and magnesium concentration to prevent zeolite deposition on fuel;
- Ammonia concentration to prevent resin degradation and to evaluate impact on Carbon-14;
- Nitrogen concentration to evaluate the impact on Carbon-14;
- Gamma Ray Spectrometry of Corrosion product monitoring for detection of isotopes;
- Global Gamma to evaluate the global radiological state of the plant;
- Global Alpha for alpha risk prevention and for waste management;
- Alpha Spectrometry to prevent alpha risk;
- Tritium activity to meet the discharge limits and control the dose rate (fuel pool activities).

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b

For the complementary parameters which will assist the chemistry staff in interpreting variations in the system chemistry, the expected values will be defined in operating procedures. These parameters are as follows:

- FW oxygen and hydrazine concentrations to confirm the reducing medium to prevent material integrity risk;
- FW amine concentrations to obtain the target  $\text{pH}_{25^\circ\text{C}}$ ;
- FW Iron concentration to evaluate the deposition risk in the SGs;
- FW conductivity to monitor conditioning and impurities;
- SG  $\text{pH}_{25^\circ\text{C}}$  to confirm the conditioning and identify a potential pollution;
- SG chlorides, sulphates, silica concentration to identify potential pollutions;
- Suspended solid concentrations to evaluate the deposition risk;
- CEX sodium and oxygen concentration and cation conductivity to identify potential leaks.

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<sup>6</sup> The required pH<sub>25°C</sub> will be obtained solely by the addition of trisodium phosphate

## SUB-CHAPTER 5.5 – REFERENCES

External references are identified within this sub-chapter by the text [Ref-1], [Ref-2], etc at the appropriate point within the sub-chapter. These references are listed here under the heading of the section or sub-section in which they are quoted.

### 1. PRIMARY SIDE SYSTEM WATER CHEMISTRY

#### 1.1. CLAIMS AND ASSOCIATED ARGUMENTS

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##### 1.1.1. Contribution to Safety Functions

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[Ref-2] Identification of the 'Level 2' Chemical and Radiochemical Parameters, as part of the RGE Rules of the Flamanville EPR. EDECME100781 Revision A. EDF. November 2010. (E)

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[Ref-1] EPR FA3 – Report on Identifying Chemical and Radiochemical Parameters for Operating Technical Specification (Level 1 Specifications). ECEF091642. Revision B1. EDF. October 2010. (E)

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[Ref-1] A Tigras. Analysis of UK EPR™ Source Term: Identification, Quantification and Characterisation. ECEF110448 Revision A. EDF. July 2011. (E)

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#### **1.2.2.1. Identification and Quantification of Evidence**

##### **1.2.2.1.1. Material Integrity Evidence**

[Ref-1] Pressurized Water Reactor Primary Water Chemistry Guidelines, EPRI Report 1014986 Revision 2. EPRI. December 2007. (E)

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##### **1.2.2.1.2. Radiation Field / Crud Management / Availability**

[Ref-1] Status on Crud Monitoring and Acceptability. FS1-0001318 Revision 1.0. AREVA. July 2010. (E)

[Ref-2] A Tigras. Analysis of UK EPR™ Source Term: Identification, Quantification and Characterisation. ECEF110448 Revision A. EDF. July 2011. (E)

[Ref-3] A Tigras, M Bachel. Corrosion product characterization under PWR/EPR primary coolant conditions: thermodynamic assessments and power plant feedback. ECEF111022 Revision A. EDF. July 2011. (E)

[Ref-4] Reduction in Primary Circuit Radioactivity SFAIRP Based Upon the Primary Circuit Chemistry. NEEMF DC 143 Revision C. AREVA. March 2011. (E)

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[Ref-2] Chemistry and Radiochemistry monitoring at UK-EPR primary coolant. ECEF110140 Revision A. EDF. March 2011. (E)

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[Ref-2] Shutdown and start-up primary coolant chemistry/radiochemistry strategy for UK-EPR. ECEF110142 Revision A. EDF. March 2011. (E)

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