

**UK ABWR**

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# UK ABWR Generic Design Assessment

## Generic PCSR Chapter 23 : Reactor Chemistry



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## **23.1 Introduction**

This chapter provides a description of the primary system water chemistry and the chemistry of auxiliary systems. The material selection for primary systems is a key parameter to ensure the safe operation of the plant. The chemistry is optimised to ensure the integrity of fuel and structural materials and to reduce radiation fields based on the selected materials. The main chemistry parameters are also described and justified in this chapter, including the design optimisation which provides the means to achieve the objectives of material and equipment integrity, radiation protection, minimisation of environmental impact and flammability risk control.

## **23.2 Primary System Water Chemistry**

Primary cooling water consists of condensate water, feedwater and the reactor water. Some reactor water is converted to steam by nuclear heating, passed through the turbine and the steam is condensed to water at the condenser. Gaseous and volatile species and extremely small amounts of other impurities are transferred with steam to the turbine system. Most of the gaseous and volatile species are extracted with leakage air at the condenser to the off-gas system. Condensate water contains dissolved oxygen and corrosion products originating from turbine and condenser materials. It is purified by the condensate filter and demineralizer to become feedwater. Feedwater is heated up by the feedwater heaters and supplied to the Reactor Pressure Vessel (RPV) with a small amount of corrosion products originated from the heater drain, heater tubes, valves and piping of the feedwater line. Feedwater flow rate is about 17 times reactor water volume per hour so that the reactor water chemistry mostly depends on the feedwater chemistry and the reactor water clean up system. Reactor water chemistry control is usually conducted through control of the feedwater.

Condensate water chemistry is monitored but not actively controlled. So, feedwater chemistry and reactor water chemistry are controlled and described separately in this section. An outline of ABWR systems interfaces with the discipline of reactor chemistry is described in the preliminary safety report on reactor chemistry [Ref-1].

### **23.2.1 Description of Water Chemistry Regime**

As boiling in the reactor core has a tendency to concentrate the impurities in the reactor water, high water purity is used as the fundamental chemistry for all BWRs including ABWR to maintain the integrity of fuel and structural materials as well as to reduce dose rate and radioactive waste. However, oxygen and hydrogen peroxide are generated by water radiolysis in the reactor core, which accelerate the corrosion of structural materials. These oxidizing species are known to increase Stress Corrosion Cracking (SCC) generation and crack propagation rates. Though UK ABWR is made of SCC resistant materials and adopts stress relief measures, there is still a slight residual potential of SCC during the design life of 60 years as described in Ref-1. Hydrogen water chemistry (HWC) with noble metal chemical addition (NMCA) is known to mitigate SCC as a proven technology and will be utilized for UK ABWR. In this regard, it has been reported that the SCC of reactor internals in actual BWRs was suppressed by the application of the noble metal technology [Ref-2].

In order to reduce dose rate under HWC conditions, depleted zinc injection is also widely used and will be employed for UK ABWR. Optimum feedwater iron concentration control realizes the low

soluble Co-58 and Co-60 concentrations in the reactor water, which result in the low dose rate of components and piping.

Oxygen injection into the feedwater is used for the most of BWR plants to reduce corrosion of carbon steel of the feedwater line, which enables maintenance of an optimum iron concentration.

In addition to high water purity and oxygen injection into the feedwater; optimum iron concentration control, hydrogen injection, Pt injection and depleted Zn injection constitute the base water chemistry conditions for UK ABWR in order to maintain fuel and structural materials integrity, a lower radiation exposure and a lower generation of radioactive waste.

### **23.2.2 Claims and Associated Arguments**

The claims associated with the primary system water chemistry are as follows:

- The chemistry regime for UK ABWR maintains the integrity of the fuel and structures in the reactor pressure vessel and reactor coolant system boundary.
- Radiation source term is minimised so far as is reasonably practicable by the combination of material selection and optimum water chemistry control to reduce operational radiation exposure.

These claims are justified by the arguments described in the following sections.

#### **23.2.2.1 Material Selection for Source Term Reduction**

The claims associated with material selection from the viewpoint of source term reduction are as follows.

- Cobalt source material is minimised by the use of low Cobalt content alloys and alternative materials to Cobalt base alloys so far as is reasonably practicable.
- Low alloy steel is used where water chemistry conditions can not be controlled adequately.

Radiation exposure is directly related to the dose rate of components and piping which contact with the reactor water. Cobalt-60, Co-58 and Mn-54 are the main contributors for dose rate in UK ABWR. Stainless steel and nickel base alloy generally contains a certain amount of cobalt as an impurity, which results in the increase of radiation exposure by dissolution of these materials. Low cobalt content stainless steel and nickel base alloys, whose impurities are controlled at the fabrication stage, are applied to reduce cobalt generation. Stellite, which is a cobalt based alloy, is applied to valve seat etc. because of its good properties of wear-resistance and corrosion resistance. However, it becomes

worn and eroded by long-term usage. Fines caused by the wear process are fed into the reactor and activated, which results in the increase of radiation exposure. So, alternative materials to Stellite, which are usually either nickel based alloys or iron based alloys, are also applied to the affected parts such as pin and roller of control rod.

The reactor components to which the low cobalt content materials are applied are selected by evaluating a dissolution amount of cobalt into the reactor water. Basically components having a large surface area are subject to the application of low cobalt materials. As for a cobalt based alloy, its use is restricted to the limited places where wear and corrosion resistance is required and substitute for a cobalt based material does not exist. The typical example is the large scale valve seat.

The source of Mn-54 is predominantly iron crud. To minimise the input of iron crud into the RPV, UK ABWR adopts low alloy steel for heater shell, cross around piping and extracted steam piping instead of carbon steel, where water chemistry control can not be applied due to the system configuration or lack of effective countermeasures. The amount of corrosion in the heater drain system reduces to less than 1/10 by adopting low alloy steel [Ref-3]. Weather resistant steel which is a kind of low alloy steel is applied to the condenser for the same reason.

### **23.2.2.2 Feedwater Chemistry**

The claims associated with feedwater chemistry are as follows:

- Feedwater chemistry control minimises corrosion of carbon steel piping in the feedwater system as low as reasonably practicable.
- Impurities (except for iron) in the feedwater are minimised as low as reasonably practicable.
- Iron concentration in the feedwater is controlled to minimise the generation of source term.

#### **23.2.2.2.1 Power operation**

The claims associated with feedwater chemistry during power operation are as follows.

- Oxygen concentration is controlled to prevent Flow Accelerated Corrosion (FAC) in the feedwater line.
- Dissolved oxygen in the feedwater has little effect on the reactor water.
- Iron concentration in feedwater is optimised to reduce radioactive Co concentration in the reactor water.
- In order to make feedwater pure, most of the impurities are removed by the condensate filter and demineralizer from the condensate water and low pressure heater drain water.

- Dissolved oxygen in the feedwater and condensate system should be controlled to greater than 15 ppb in order to prevent FAC.

Feedwater chemistry is related to the integrity of the feedwater system components and piping as well as the reactor water chemistry. The basis of the feedwater chemistry is adoption of high purity water in order to keep the high purity of the reactor water.

In order to make feedwater pure, most of the impurities are removed by the condensate filter and demineralizer from the condensate water and low pressure heater drain water. Impurities in feedwater largely affect the reactor water chemistry.

The amount of general corrosion product, referred to as crud, are controlled in the feedwater and condensate system as input of too much crud into the core region may create harmful effects for fuel structural material integrity by accumulating on the fuel cladding and thereby decreasing thermal conductivity. When the concentration of dissolved oxygen is extremely low, the amount of corrosion increases rapidly because an oxide film can not be formed and maintained on the carbon steel. This phenomenon is referred to as FAC. Since FAC correlates with general corrosion, the prevention of both crud formation and FAC of carbon steel in the feedwater and condensate system depends on the same countermeasures. It is known from the experimental results that a concentration of dissolved oxygen of more than 15 ppb can suppress both phenomena [Ref-4]. However, the concentration of dissolved oxygen is normally less than 10 ppb in BWRs because dissolved oxygen in the condenser is removed by vacuum deaeration. This concentration of dissolved oxygen leads to FAC. Taking into consideration the above fact, the dissolved oxygen in the feedwater and condensate system should be controlled to greater than 15 ppb.

Oxygen in the feedwater line increases the SCC risk of core structural materials. However, dissolved oxygen concentration in the reactor water of UK ABWR (and other BWRs), around 250 ppb, is mostly produced by water radiolysis reactions in the RPV. So, dissolved oxygen concentration to prevent FAC in the feedwater system does not adversely affect SCC risk in the RPV.

Nickel ion to iron crud ratio (Ni/Fe ratio) in the feedwater becomes high when the above countermeasures are applied. In this case, Nickel ions are deposited on the fuel surface as nickel monoxide. In addition, the cobalt ions, Co-58 and Co-60 are also deposited there as monoxides as the chemical property of cobalt is similar to that of nickel. Solubility of these monoxides is relatively high and these monoxides are dissolved in the reactor water again, which results in the increase of radioactive concentration of Co-58 and Co-60. The amount of iron crud fed into the reactor can be

increased by bypassing the condensate filter, which enables control of the Ni/Fe ratio. In this condition, nickel ions and cobalt ions are deposited on the fuel surface as nickel ferrite and cobalt ferrite, whose solubility is lower than that of these monoxides. As a result, the concentration of ionic radioactive species can be maintained low.

If a condenser tube leakage occurs in a plant in which sea water is used as cooling water, the impurities such as chloride and sodium flow into the coolant. The occurrence of the leakage is promptly detected by conductivity measuring equipment located in the condensate system and feed water system. In the case of a small leak, the inflowed impurities are captured by the condensate demineralizer so that plant operation can be continued. On the other hand, if a large amount of leakage occurs, the impurities cannot be purified by the demineralizer and may affect the structural integrity of the reactor components. In this case, the plant must be shutdown and the damaged condenser tube repaired.

#### **23.2.2.2.2 Outage and start-up**

The claims associated with feedwater chemistry during outage and start-up are as follows.

- Carbon steel piping is kept under the optimum environment during outage.
- Corrosion products in the feedwater line generated during the outage are removed before start-up.

Water in the piping of the feedwater and condensate system is drained and the system dried during the outage to reduce the corrosion of structural materials if the outage is of an extended duration. If drainage and/or dry conditions are difficult to achieve, the system is filled with demineralized water. Before start-up, the coolant in the feedwater and condensate system is purified by re-circulation through the condensate filter to remove crud which is generated during the outage. A feedwater recirculation line, which is branched from the upstream of the feedwater flow element at the final feedwater heater outlet and connected to the condenser, is provided to reduce the ingress of impurities into the reactor and to ensure feedwater quality at plant startup or shutdown. A condensate recirculation line, which is connected to the condenser, is provided to ensure the minimum required flow rate of cooling water for the Steam Jet Air Ejector (SJAE) condenser and the Gland Steam Condenser (GSC), and the minimum flow rate of the Low Pressure Condensate Pump (LPCP).

#### **23.2.2.3 Reactor Water Chemistry**

The claims associated with reactor water chemistry are;

- Impurities in the reactor water are maintained as low as reasonable practicable by the appropriate CUW operation and feedwater chemistry control.
- The reactor water chemistry mitigates SCC of the reactor internals and materials forming the reactor coolant pressure boundary.

The reactor water clean up system (CUW) is continuously operated to remove impurities and radioactive corrosion products to maintain high purity reactor water except during maintenance and inspection of CUW in the outage. Appropriate CUW operation ensures the low concentration of chloride and sulfate which are harmful species for SCC. If CUW is not available during outage, the purification system of SFP is used because the SFP and the reactor are connected through a pool gate.

#### 23.2.2.3.1 Start-up

The claim associated with reactor water chemistry during start-up is;

- Deaeration operations before start-up ensures mitigation of SCC.

Before start up, the concentration of dissolved oxygen in the coolant is saturated because the primary system is exposed to air. There is a period during which the transfer efficiency of oxygen into the main steam is low because steam generation during start up is lower than that during operation. High oxygen concentrations may be experienced during start up, which is undesirable for SCC prevention. To avoid this situation, deaeration is conducted and the dissolved oxygen concentration is controlled above a coolant temperature of 100 °C. In deaeration, the concentration of dissolved oxygen in the reactor water is reduced to about 10 ppb by vacuum deaeration, which maintains the integrity of the structural materials during the heating-up period.

#### 23.2.2.3.2 Power operation

The claims associated with reactor water chemistry during power operation are as follows:

- Hydrogen injection with platinum into the reactor water mitigates SCC of structural materials.
- Depleted zinc injection reduces the dose rate of primary cooling system components and piping.
- Adequate zinc injection has no adverse effect on fuel and structural material integrity and little impact on source term.
- Adequate platinum injection has no adverse effect on fuel integrity and little impact on source term.

Since the recognition of Inter Granular Stress Corrosion Cracking (IGSCC) in BWR structural materials, a number of remedies have been employed for UK ABWR that address the three key contributing aspects of this phenomena: materials (selection and fabrication processes), tensile stress and environmental factors. Reactor water becomes a reducing environment by adoption of HWC or HWC + NMCA because oxidizing species such as oxygen and hydrogen peroxide are consumed by the recombination reaction with hydrogen. This means that Electrochemical Corrosion Potential (ECP) reduces through adoption of HWC or HWC + NMCA, which results in the decrease of crack growth rate. A low ECP environment can be achieved by addition of a smaller amount of hydrogen in HWC + NMCA regimes. In this case, the dose rate in the main steam line, which is caused by radioactive nitrogen (N-16) in volatile form such as ammonia (NH<sub>3</sub>), is kept low due to the suppression of volatile elements [Ref-5]. This phenomenon can be understood by the shift of the stable nitrogen compound as NO<sub>2</sub> → NO → NH<sub>3</sub> depending on the amount of hydrogen in the coolant. Mitigation of crack initiation is achieved by material and manufacturing process improvement and stress reduction.

Zinc injection is one of the approaches to reducing dose rate through the reduction of the Co deposition rate on piping and component surfaces. The effect of zinc in suppressing the buildup of Co-60 inside oxide films was first recognized by the observation that plants with high zinc concentrations in reactor water had less radiation dose rates from piping. Through experimental and field studies, it was found that amounts of soluble zinc in reactor water reduced Co-60 buildup in the corrosion films on piping and components by promoting the formation of a protective oxide film of spinel structure. Radiation dose rates are lowered since Zn is favored for incorporation into the oxide film relative to Co-60. While Natural Zinc Oxide (NZO) is effective in reducing radiation fields, activation of the Zn-64 (48% of NZO isotopic composition) to form Zn-65 contributes to radiation fields and low level wastes. Consequently, Depleted Zinc Oxide (DZO), that is, zinc depleted in Zn-64, is commonly used for zinc injection application in UK ABWR. When DZO is coupled with a low iron input and cobalt alloy control, low shutdown dose rates can be obtained [Ref-6].

Due to zinc injection, it is necessary to consider the effect of zinc on the fuel integrity because injected zinc is deposited not only on the piping surface but on fuel cladding. Since injected zinc is deposited on the fuel cladding as zinc ferrite; zinc concentration and iron concentration are important parameters for fuel integrity. According to EPRI water chemistry guidelines for the environmental mitigation, it is recommended that zinc concentration should be less than 0.4 ppb and iron

concentration should be less than 1.0 ppb in feedwater, of which restriction has been proposed on the basis of many plant data [Ref-7].

#### **23.2.2.3.3 Shutdown**

The claims associated with reactor water chemistry during shutdown are;

- Low temperature shutdown cooling operation ensures dose rate reduction in the residual heat removal system so far as is reasonably practicable.
- Purification operation of Residual Heat Removal (RHR) prior to placing the system in-service reduces the input of corrosion products into the reactor.

Radioactive crud concentration in the reactor coolant spikes during the decreasing pressure and temperature phases during shutdown. Crud may be deposited in stagnant areas such as RPV bottom and instrument piping, which results in the formation of hot spots. Therefore, soft shutdown operation is applied for the purposes of radiation exposure reduction. The rate of decreasing pressure and temperature is controlled during shutdown operations.

Furthermore, the concentration of radioactive species increases due to the decrease of corrosion product deposition on the fuel surface in the shutdown state. Radioactive species are incorporated into the hydroxide form on Residual Heat Removal (RHR) system piping, which is used for reactor cooling during the shutdown state. As a result, the dose rate of RHR piping increases. The degree of incorporation into the hydroxide is mainly dependent on the in-service temperature. To reduce the incorporation of radioactive ions into the RHR piping, in-service temperature is controlled.

Since the piping in the RHR system is made of carbon steel and the system is usually filled with pure water, corrosion products will be generated. To reduce the crud input from the system to the reactor, purification is conducted prior to placing the system in-service. In particular, detachment of the crud is conducted using the test line of the suppression pool. After that, water in the system is replaced by make up water.

#### **23.2.2.3.4 Outage**

CUW and FPC purification systems are used during the outage (except for ISI and their maintenance periods), which results in a reduction in radiation exposure, in order to maintain low radioactive nuclide concentrations in the reactor water, separator-dryer pool water, reactor well water and spent fuel pool water, which are connected as one pool.

**23.2.2.3.5 Iodine and Alpha Risks**

When there are cases of extremely low uranium deposits (known as tramp material) on the outer surface of fuel cladding at the time of fuel production, and such a fuel rod is loaded in the core, radioactive iodine may be detected in the reactor water and the steam. Therefore, the fuel rod is inspected at the time of production, and it is confirmed that the quantity of adhesion of uranium is sufficiently low.

In a pin failure event, fission products such as noble gas, iodine and cesium will be released into the reactor coolant water. However, soluble and particulate radionuclides were held in water phase and removed by reactor water clean-up system (CUW). Uranium and other actinides can be deposited around the circuit. Only noble gas and iodine gas could be discharged to the off gas system.

**23.2.2.4 Primary System Water Chemistry Optimisation (ALARP)**

The water chemistry regime for UK ABWR is optimized to maintain plant safety. When one chemistry parameter is optimized for one purpose, it may have a negative effect on another variable. For example, HWC is effective in mitigating SCC, while high hydrogen injection results in high N-16 dose rates in the turbine system. In order to satisfy the purposes of reactor chemistry including fuel and structural material integrity, radiation exposure reduction and radioactive waste generation reduction; not only water chemistry control methods, but also material selection is important for overall chemistry optimization.

Though UK ABWR is made of SCC resistant materials and adopts stress relief measures, residual SCC potential for the 60 years plant life is further reduced through the use of HWC and platinum injection.

Hydrogen injection is a method to reduce dissolved oxygen and hydrogen peroxide concentrations in reactor water. HWC effects on the plant depend upon the hydrogen injection rate. Lower injection rates result in less mitigation effect on SCC and less side effects on the plant. Higher concentrations in feed water will be necessary to obtain sufficient SCC mitigation effect, which will cause higher dose rates around the turbine system during operation and higher radiation exposure to plant personnel.

Noble metal chemical addition was developed to reduce the N-16 side effects of HWC. This combination of water chemistry enables a high SCC mitigation effect with little N-16 dose rate

increase. However, it is predicted that this water chemistry increases the carbon steel piping dose rates such as those of the CUW and high temperature areas of RHR piping. Though there are some methods for dose rate reduction of carbon steel (CS) in NWC conditions, there are none in HWC with or without NMCA conditions.

Zn injection is the more effective dose rate reduction method under a reducing environment for stainless steel piping. However, it has little reduction effect for CS. Material changes to CUW piping from the existing ABWR are being considered and will be elaborated on in steps 3 and 4. This combination resolves the dose rate problem of CUW piping. However the SCC potential of this piping arises due to the material change from CS to stainless steel. A considerable SCC potential decrease and a significant crack growth rate reduction for reactor internals and parts of the pressure boundary of RPV are expected, while a small SCC potential increase for RPV external stainless steel piping, additional dissimilar welding and the potential increase of CUW piping length inside the PCV due to a larger thermal expansion rate are predicted. However, CUW piping of stainless steel is widely used in the US and no SCC for CUW piping of stainless steel has been reported so far. Approximately 4 times higher dose rate is predicted for CS under reducing conditions compared to the NWC conditions and is not tolerable for inspection and maintenance during the outage. The combination of hydrogen, platinum and zinc injection for UK ABWR water chemistry control with the CUW piping of stainless steel will be considered and the case presented during steps 3 and 4 of GDA. So in addition to high water purity and optimum iron concentration control, HWC, Pt and Zn injections are the base water chemistry conditions for UK ABWR. The option of material change of the CUW piping will be finalized after detailed evaluation of SCC mitigation, radwaste, structural integrity and dose rate and presented during later steps of the GDA process.

### **23.2.3 Evidence Supporting the Claims and Arguments**

The evidence supporting the claims and arguments will be developed and demonstrated in later GDA steps.

### 23.3 Spent Fuel Pool Water Chemistry [Ref-1]

The pool itself is made of reinforced concrete with stainless steel lining and a sufficient amount of coolant is maintained to keep the fuel cool under anticipated conditions. The fuel is arranged in racks of borated stainless steel immersed in the pool. In this system, coolant is re-circulated for purification and cooling. RHR can be aligned in parallel with the SFP cooling system in such cases where all spent fuel is removed to the SFP, creating a higher heat load.

SFP is separated from the reactor well by the pool gate, and in the fuel exchange work, the gate is opened and filled with water to connect SFP with the reactor core enabling the fuel carriage from the core to SFP and *vice versa* under the water environment as described in Chapter 19.4.

#### 23.3.1 Description of Water Chemistry Regime

The purposes of water chemistry management of the SFP are primarily to maintain the fuel integrity in the storage pool, including the integrity of the storage rack and pool itself and to suppress the radioactivity level in the pool. Furthermore, as the SFP is connected with reactor core during refueling, maintaining the specified water quality of the reactor water is required for the SFP water. For this purpose, coolant is purified and its temperature is controlled during normal operation. Coolant purification has two purposes: one is to protect the fuel, fuel rack and pool structure materials from corrosion and the other is to maintain the clarity of coolant for viewing the fuel assembly under water. At the same time, the radioactivity emanating from spent fuel is removed by the purification system.

#### 23.3.2 Claims and Associated Arguments

The claims associated with spent fuel pool water chemistry are;

- The chemistry of the spent fuel pool contributes to maintaining the integrity of the fuel and spent fuel pool structures and liner during refueling, normal operations and storage.
- The chemistry regime of the spent fuel pool ensures that occupational radiation exposure (ORE) is kept ALARP.

Basically as the temperature of the SFP water is the ambient one, the corrosion of the related materials in the SFP is not of concern. However, by suppressing the harmful elements for fuel and structural materials in the SFP and reactor, further protection against material damage can be established.

Two loops of filter demineralizer (F/D) for coolant purification and radioactivity removal and two loops of heat exchangers for temperature control are provided in UK ABWR. Considering the coolant water of the SFP during the outage is mixed with the reactor water during refueling, the water chemistry of the SFP is required to be the same as or better than the reactor water chemistry in the reactor shut-down stage. Clarity of coolant is required especially during refueling.

In the recirculation loop of the SFP, several sampling points are set to monitor the water quality of the coolant. Sampling Points are located at the inlet and outlet of the F/D to enable monitoring of F/D performance. For the purpose of detecting the leakage from heat-exchanger, one sampling point is set downstream of a heat-exchanger, one sampling point is set downstream of heat-exchangers.

### **23.3.3 Evidence Supporting the Claims and Arguments**

The evidence supporting the claims and arguments will be developed and demonstrated in later GDA steps.

## **23.4 Component Cooling Water Chemistry [Ref-1]**

The auxiliary component cooling systems consist of multiple, independent systems, which are classified by usage and supply area. The system, in general, comprises the closed loop in which coolant is re-circulated to remove heat emanating from equipment in the component room. The re-circulated coolant releases the heat ultimately to sea water through the heat exchanger. In the system, a chemical addition tank is installed for injecting anti-corrosion chemicals into the coolant. Coolant is added to the system by supplying makeup water (MUW) to the surge tank.

As a constituent material, carbon steel is used for the piping. Materials with low thermal resistance are applied to the heat exchanger tubes.

It should be noted that detailed design of the component cooling water system (including material selection and heat exchanger type) is ongoing, and the final design will be presented during the forthcoming steps of the GDA process.

### **23.4.1 Description of Water Chemistry Regime**

The purpose of water chemistry management is to prevent the equipment and piping of the system from corrosion damage, which could result in the decrease of equipment performance such as stable coolant supply and heat exchange efficiency.

### **23.4.2 Claims and Associated Arguments**

The claim associated with component cooling water chemistry is;

- The chemistry of component cooling water minimizes the corrosion of its system materials to maintain their integrity and heat transfer function.

Suppression of material corrosion in the system is achieved by adding anti-corrosion chemicals. Chemicals such as chromate used to be a standard chemical. However, it has been pointed out that the use of chromate is harmful for environment. For this reason, sodium nitrite is the most favorable chemical to be used for this purpose. Its validity has been demonstrated through operational experience. Nitrite is known to reduce corrosion of carbon steel. Though nitrite may be oxidized by the presence of micro-organisms, this concern can be avoided by managing water chemistry so as not to contaminate the loop with micro-organisms in the closed system. The targeted nitrite concentration is greater than 200 ppm.

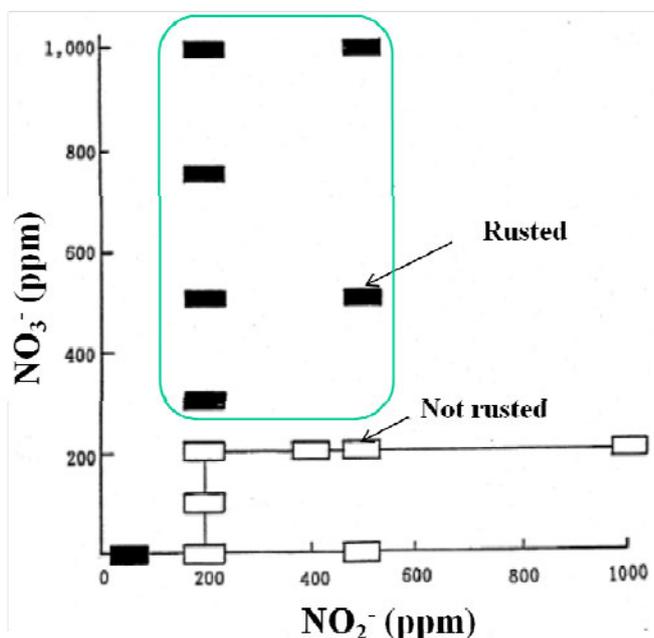
In the case of a system in which copper containing materials are used, water chemistry is controlled to maintain the low solubility of copper oxides by using the pH control. In actual management, pH of the coolant is maintained to ensure that a low solubility of copper oxides can be established. pH can be adjusted to the proper value by adding sodium hydroxide via the chemical addition tank. Normally, in addition to the pH control, the chemicals of the nitrite family which contain the anti-corrosion chemicals for copper containing materials are applied to strengthen the effectiveness of the corrosion reduction of the copper family materials.

In case the nitrite concentration decreases, anti-corrosion chemicals can be replenished. If nitric acid concentration is increased, the coolant can be blown down and the loop re-filled with demineralized water.

### 23.4.3 Evidence Supporting the Claims and Arguments

Figure 23.4-1 shows the effective range of nitrite as an anti-corrosion reagent under co-existing nitrate ions.

As can be seen from the figure, the presence of more than 200 ppm nitrite ions suppresses the corrosion of carbon steel even though the corrosive nitrate ions co-exist up to 200 ppm.



**Figure 23.4-1 : Effective Range of Nitrite as an Anti-Corrosion Reagent Under Co-Existing Nitrate**

Figure 23.4-2 reveals the experimental result on the solubility change of CuO and Cu(OH)<sub>2</sub> with respect to pH. The minimum of the solubility exists at around pH=9, hence, accommodating the pH at the desirable range, i.e., around pH 9, is effective to suppress the dissolution of cuprous materials.

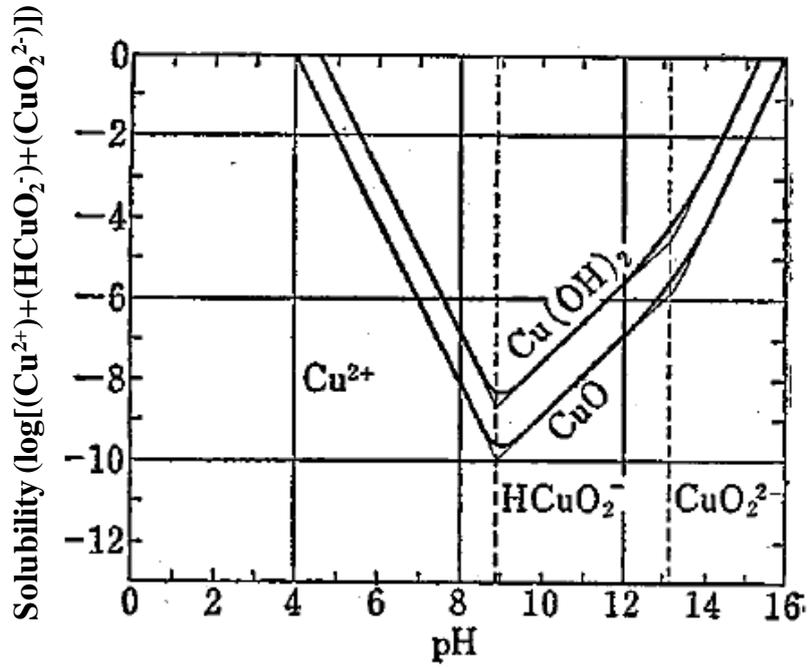


Figure 23.4-2 : Solubility of  $\text{CuO}$  and  $\text{Cu(OH)}_2$  [Ref-2]

## 23.5 Suppression Pool Water Chemistry [Ref-1]

The Suppression Pool (SP) is a large pool located at the bottom of the Pressure Containment Vessel (PCV) and has the function of suppressing over pressure by condensing steam released from the reactor into the drywell in the case of a Loss Of Coolant Accident (LOCA). Other main functions of the pool are:

- (1) coolant source during RHR system surveillance operation,
- (2) coolant source for filling the reactor well during outage,
- (3) containment of iodine species in case of large scale fuel failure after LOCA,
- (4) coolant source during LOCA.

The SP is made of stainless steel for the part immersed in water and coated carbon steel for the dried part. Coating of carbon steel by a suitable paint is effective to prevent the corrosion in moist atmospheres. For water purification, the SPCU is used. In order to suppress the corrosion of structural materials, countermeasures are applied as described in Chapter 23.5.1.

### 23.5.1 Description of Water Chemistry Regime

The purpose of water chemistry management for the SP is described as follows:

- (1) effective suppression of volatilization of iodine species by containing the species in the coolant during a LOCA,
- (2) supply of pure water into the reactor vessel during outages.

For suppression of iodine release outside of the PCV during a LOCA event, pH control of the suppression pool coolant is an important issue, because with a higher coolant pH, more iodine species form as fission products are retained in the liquid phase. Other radionuclides released during LOCA are dissolved or deposited in the SP and thereby removed.

When the coolant is used for filling the reactor well during outages, the coolant can be demineralized to a quality similar to the spent fuel pool coolant by fuel pool cooling system.

### 23.5.2 Claims and Associated Arguments

The claim associated with suppression pool water chemistry is;

- Suppression pool chemistry reduces the release of radioisotopes from the Reinforced Concrete Containment Vessel (RCCV) so far as is reasonably practicable during accident scenarios.
- Suppression pool water is maintained pure during normal operation to supply water for the RHR system surveillance operation and to fill up the reactor well during outages.

Since, from the viewpoint of safety analysis, the gas-liquid distribution coefficient of suppression pool coolant should be maintained to be more than 100, pH of the coolant should be managed so that it is greater than 5.5. As the coolant of UK ABWR is demineralized water and the suppression pool is open to the air, the pH of the suppression pool water is normally around 5.3 due to the dissolution of carbon dioxide. Considering the situation that the iodine concentration in the liquid phase during a hypothetical accident is conservatively expected to be around 1.2 mg/L, if the pH is greater than 5.5 the iodine partition coefficient can be greater than the targeted value 100 with sufficient margin. If the pH of the coolant is below the value, replacement or purification of the coolant by fuel pool cooling system or makeup water can be carried out.

During normal operation, water in the SP is used for the RHR system surveillance operation and to fill up the reactor well at the beginning of the outage. The water quality for these purposes must be pure. So, SP water is maintained to set levels during normal operation by the SPCU.

### 23.5.3 Evidence Supporting the Claims and Arguments

Figure 23.5-1 shows the relationship between the gas-liquid partition coefficient of iodine and pH. The curve of the gas-liquid partition coefficient of iodine for each coolant pH is depicted with respect to the iodine concentration in coolant. As can be seen, if pH of the coolant is greater than 5.5, a sufficiently greater value of gas-liquid partition coefficient than 100 is achieved at the iodine concentration in coolant, which corresponds that occurring during hypothetical accident scenarios.

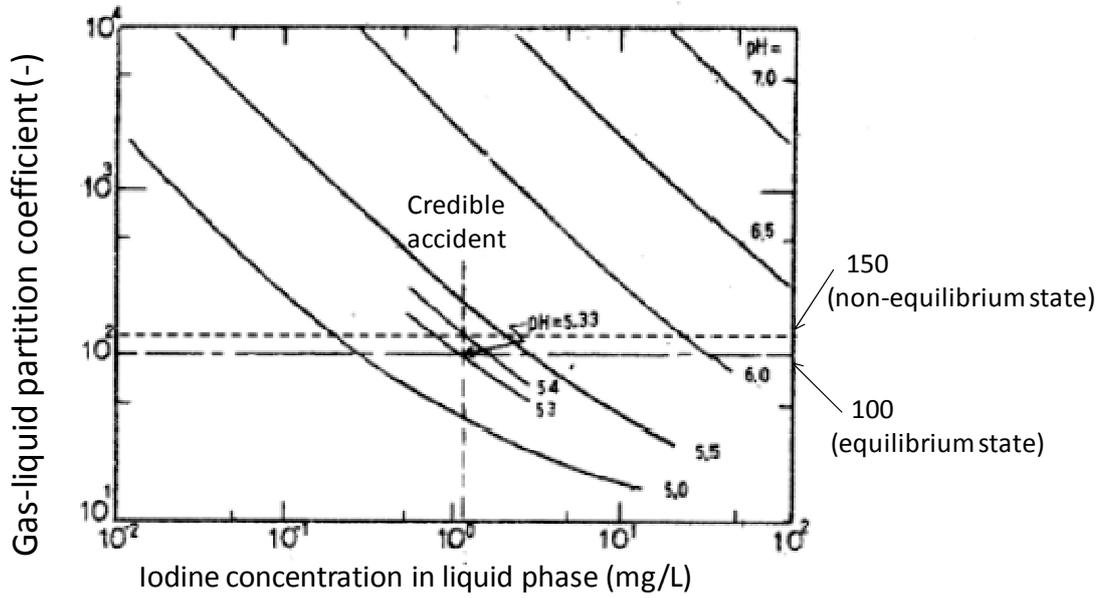


Figure 23.5-1 : Relationship Between Partition Coefficient and pH [Ref-2]

## **23.6 Stand-By Liquid Control System**

The safety claim for the Standby Liquid Control System (SLC) from a chemical point of view is described below in this section. Claims from a reactor-safety point of view are described in Chapter 12. This subsection will be updated in later stages of GDA.

### **23.6.1 Description of SLC Chemistry**

The SLC function is to supply neutron absorber solution into the reactor if the reactor cannot be shut down in the event of an ATWS (Anticipated Transient Without SCRAM) or maintained sub-critical with the control rods. Sodium pentaborate solution is used as a neutron absorber. Further information on the SLC can be found in Chapter 12.

### **23.6.2 Claims and Associated Arguments**

Claims associated with the SLC chemistry are:

- To ensure sufficient neutron absorber can be injected into the core to maintain the reactor sub-critical in the event of an ATWS.
- To maintain the integrity and availability of the SLC during standby conditions.
- To minimise corrosion of fuel and to help preserve structural material integrity in case of SLC initiation.

The neutron absorber is sodium pentaborate solution. It is prepared by dissolving sodium pentaborate in demineralized water from the Makeup Water Purified System. Sodium pentaborate solution is stored in the SLC Storage Tank. The concentration and volume of solution stored in the tank are determined from the concentration of natural boron required to take the reactor sub-critical under cold conditions in the event of an ATWS and will be presented in later stages of GDA. The minimum concentration of natural boron in the reactor water will be fixed once the fuel design is finalised and presented in the later stages of GDA.

Electrical heaters are installed in the storage tank to maintain a solution temperature within an adequate range to prevent precipitation of the sodium pentaborate from the solution during storage. Temperature and level in the SLC storage tank are indicated in a local panel and the liquid level is also indicated in the Main Control Room. High or low temperature, or high or low liquid level, causes an alarm in the Main Control Room. The solution in the tank is sampled to confirm that the solution concentration is within an adequate range.

The SLC Storage Tank, connected pipework and valves are designed to prevent precipitation of sodium pentaborate that causes clogging by minimising the distance of the suction lines between the SLC Storage Tank and the tank outlet valves.

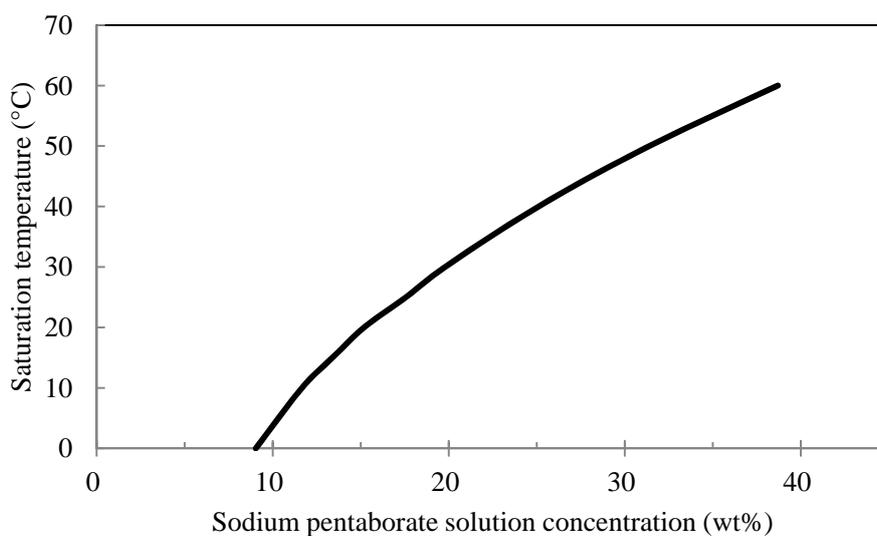
The SLC piping and components are designed to maintain their integrity for 60 years plant life in consideration of the control of water quality in the tank and piping, the selection of appropriate materials and foreseen replacement of components.

The pH of sodium pentaborate solution is alkaline and there are no materials in the primary cooling system susceptible to corrosion under alkaline conditions. Therefore the SLC minimizes corrosion of fuel and helps preserve structural integrity in case of SLC initiation.

In the event of inadvertent actuation of the SLC, the Reactor Water Clean-up System (CUW) is utilised to remove injected soluble boron in the reactor after stopping the SLC. The CUW, which is isolated from the primary circuit before the SLC initiation, pre-coats new resin after backwashing the CUW filter demineraliser and disposing of its spent resin before clean-up operation regarding possibility of displacement of radionuclides already removed from reactor water.

### 23.6.3 Evidence Supporting the Claims and Arguments

Figure 23.6-1 shows a relation between the saturation concentration and temperature of the sodium pentaborate solution. The tank, pumps and heaters are designed according to the characteristics with sufficient margin to prevent insufficient amount of soluble boron being available or sodium pentaborate precipitation.



**Figure 23.6-1: Sodium Pentaborate Solution Concentration and Temperature Relation\***

\*: This figure is based on the data that HGNE calculated from the solubility of the anhydrous sodium pentaborate shown in Ref-3.

## **23.7 Make-Up Water System and Condensate Storage Tank**

The Makeup Water Condensate system (MUWC) is designed to supply condensate water to components which include radioactive water and to collect waste water from the Low Conductivity Waste System. The supply water is stored in the Condensate Storage Tank (CST) as described in Chapter 16.1.4.

The major systems to which MUWC supplies water are,

- (1) Reactor core isolation cooling system(RCIC): water is fed as a primary water source,
- (2) High pressure core flooder system(HPCF): water is fed as a primary water source,
- (3) Suppression pool clean-up system(SPCU): through SPCU, water is fed to the SFP as a primary water source,
- (4) Control rod drive system (CRD): through the CRD, water is fed to the fine motion control rod drive (FMCRD), reactor internal pump (RIPs) and reactor cleanup system (CUW),
- (5) Turbine gland steam system (TGS): water is fed for steam generation source to the gland steam evaporator (GSE),
- (6) Condenser: water is fed to control the condenser hotwell water level.

### **23.7.1 Description of Water Chemistry Regime**

The purpose of water chemistry management of the MUWC/CST is to maintain the integrity of the equipment which is supplied by the system.

### **23.7.2 Claims and Associated Arguments**

The claim associated with make-up water condensate system is;

- The water quality of the MUWC/CST is controlled to help in ensuring the water quality of the primary system.

To monitor the water quality at the CST tank exit, a continuous sample line for conductivity monitoring and a manual grab sample line are incorporated.

### **23.7.3 Evidence Supporting the Claims and Arguments**

The evidence supporting the claims and arguments will be developed and demonstrated in later GDA steps.

## **23.8 Off-Gas System**

### **23.8.1 Description of Off-Gas System**

The Off-gas system holds up gases to facilitate radioactive decay, based principally on the decay rates of Xenon and Krypton and Iodine to reduce radioactive emissions. The OG recombines flammable gas (Hydrogen), which is generated from the radiolysis of reactor cooling water.

### **23.8.2 Claims and Associated Arguments**

The principal function of the OG system is to minimise the release of gaseous radioactivity such as radioactive noble gases and iodine generated by plant operation into the environment and prevent adverse effects to the plant caused by hydrogen combustion or explosion of radiolytic hydrogen produced in the reactor.

The design bases of the OG are addressed in the PCSR Chapter 18.3 “Off-gas Radioactive Waste Management System”

### **23.8.3 Evidence Supporting the Claims and Arguments**

During commercial operation (except for outages), the OG system minimises the release of radioactive noble gases to the environment. This is achieved by ensuring that the activated charcoal within the system provides sufficient hold up time for radioactive decay. Radioactive release evaluation during commercial operation is carried out. The calculated dose exposures are addressed in “Prospective Dose Modeling” [Ref-1].

The OG system reduces the risk of hydrogen combustion arising from the reaction of radiolytic hydrogen and oxygen produced in the reactor. This is achieved by providing the OG Recombiners and supplying driving steam to the 2nd stage Steam Jet Air Ejector (SJAE) so that the hydrogen concentration is below the lower hydrogen flammability limit. In addition, the OG process components on the upstream of the OG Condenser Outlet Valve are designed to withstand the pressure increase caused by a hydrogen explosion. The equipment design descriptions are addressed in the PCSR Chapter 18.3 “Off-gas Radioactive Waste Management System”.

During fault conditions such as pipe rupture or performance degradation of the activated charcoal, the OG system mitigates the release of gaseous radioactivity to the environment. The SJAE Outlet

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Valves and the SJAE Driving Steam Stop Valves are designed to be closed in a prescribed response time by remote manual operation following detection of the fault by radiation monitors in the Heating Ventilating and Conditioning System (HVAC) ducts and the OG Charcoal Adsorber discharge line. Radioactive release evaluation in the event of a fault is carried out. The calculated dose exposures are addressed in the PCSR Chapter 24 "Design Basis Analysis".

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## 23.9 Flammability Risk Control System

### 23.9.1 Description of Flammability Risk Control System

As described in the PCSR Chapter 13.2.3.1.3, flammable risk in the primary containment vessel (PCV) is reduced by the PCV Gas Control System. The PCV Gas Control System consists of the Flammability Control System (FCS) and the Atmospheric Control System (AC) with the principal role of maintaining an inert and non-explosive atmosphere within the PCV. The systems are designed to prevent build-up of hydrogen and oxygen which could be generated within the reactor and released into the PCV in a design basis event.

### 23.9.2 Claims and Associated Arguments

The principal function of the AC is to inert the atmosphere within the PCV by replacing the air with nitrogen in order to maintain the oxygen concentration in the containment at a sufficiently low level to prevent hydrogen combustion during normal operation.

The principal function of the FCS is to control the potential build-up of hydrogen from design basis metal-water reaction, which might occur beyond LOCA conditions, and from the radiolysis of water in order to limit the concentration of flammable gases (such as hydrogen and oxygen) below the flammability limits, and thus prevent an excessive increase in pressure and temperature due to the heat released by the potential reaction of these flammable gases in the PCV. The FCS limits the hydrogen and oxygen concentrations inside the PCV below 4vol% and 5vol% respectively.

The design bases and system configuration of the AC and the FCS are addressed in the PCSR Chapter 13.2.3.1.3 "Primary Containment Vessel Gas Control System".

### 23.9.3 Evidence Supporting the Claims and Arguments

The evidence supporting the claims and arguments will be developed and demonstrated in later GDA steps.

## 23.10 Sampling and Monitoring System

### 23.10.1 Description of Sampling and Monitoring System

The objective of the sampling system is to obtain the necessary data to verify plant performance for proper operation and maintenance (plant general, systems, components, etc.) by measuring plant process fluids for parameters such as conductivity, pH, dissolved oxygen, chemical impurities and radioactive species through process instruments or by chemical analysis of samples extracted from the systems at grab sampling points. The detail description of sampling and monitoring system is described in Chapter 16.2.3.

Grab sampling is useful in terms of causal analysis, cross checking and quality assurance of installed instrumentation and for extended diagnostics in a plant laboratory.

### 23.10.2 Claims and Associated Arguments

The claim associated with the sampling and monitoring system is;

- Chemistry of UK ABWR systems can be representatively sampled and monitored to ensure that the plant is maintained within safe limits.

Accurate measurement and monitoring of water quality are necessary to achieve the purpose of the monitoring of plant water chemistry. Especially, the precise measurement of species detrimental to material integrity and corrosion products is important in evaluating the structural integrity and radiation dose.

Guidelines for sampling point selection for UK ABWR are outlined as follows;

- Sampling points are selected so that confirmation of whether water quality meets criterion values can be carried out.
- At the sampling point, representative information shall be obtained for each process such as purification by demineralizer.
- If the purpose of sampling is to detect an abnormal event, the sampling point shall be set as close as possible to the relevant equipment.
- If the system is operated independently either by separation or isolation of the system, a sampling point is used for each system.
- Sampling point is set at the inlet and outlet of water-quality control equipment and purification systems.

- Sampling points shall be set at the outlet of equipment such as heat exchangers in which any leakage of the primary water may affect the water chemistry of the secondary system.

Guidelines for the instrumental and manual analysis is outlined as follows;

- Instrumental analysis is applied for items which require continuous monitoring.
- Other necessary measurements are conducted by manual analysis.
- Sampling lines for manual analysis are principally installed for each monitoring point.

Regarding radiation dose control, cobalt ion input into the reactor core plays an important role. Hence, the measurement of cobalt ion concentration is desirable. However, the measurement of cobalt is affected by the cobalt content of the sampling line, i.e., if the material of the sampling line contains a higher cobalt, the data are influenced by the cobalt dissolved from the sampling line so that the correct value of the cobalt concentration cannot be obtained. For this reason, for a cobalt sampling line, material of low cobalt content or titanium based material is used.

### **23.10.3 Evidence Supporting the Claims and Arguments**

The evidence supporting the claims and arguments will be developed and demonstrated in later GDA steps.

## **23.11 Chemistry and Radiochemistry Limits and Conditions**

This section will be completed in later stages of GDA.

## 23.12 References

### 23.12.1 Primary System Water Chemistry

[Ref-1] Chapter 2 of Preliminary Safety Report on Reactor Chemistry, GA91-9901-0041-00001

Rev.B

[Ref-2] S.Garcia and C.J.Wood, "Recent Advances in BWR Water Chemistry", Int. Conf. on Water Chemistry in Nuclear Reactor Systems, (Berlin, Sept. 15 - 18, 2008)

[Ref-3] K. Osumi et al., "Optimum Engineering for Low Radiation Exposure in BWRs and the Operating Experience", Hitachi Hyoron, vol. 68 No. 4 (1986-4) (In Japanese)

[Ref-4] E.G.Brush and W.L.Pearl, Corrosion, 28, April, 1972.

[Ref-5] H. Takiguchi, "Results of HWC Mini Test at Tsuruga-1", Proceedings of Seminar on Water Chemistry of Nuclear Reactor Systems '97, Lungtan, Taiwan, April 22-23, 1997

[Ref-6] K. Lundgren et al., Water Chemistry of Nuclear Reactor System 8. BNES, 2000.

[Ref-7] BWR Vessel and Internal Project, BWR Water Chemistry Guidelines – 2004 Revision

### 23.12.2 Spent Fuel Pool Water Chemistry

[Ref-1] Chapter 3 of Preliminary Safety Report on Reactor Chemistry, GA91-9901-0041-00001

Rev.B

### 23.12.3 Component Cooling Water Chemistry

[Ref-1] Chapter 4 of Preliminary Safety Report on Reactor Chemistry, GA91-9901-0041-00001

Rev.B

[Ref-2] G. Ito, Corrosion Science and Engineering, pp.258 (1979). (In Japanese)

### 23.12.4 Suppression Pool Water Chemistry

[Ref-1] Chapter 5 of Preliminary Safety Report on Reactor Chemistry, GA91-9901-0041-00001

Rev.B

[Ref-2] Atomic Energy Bureau, Science and Technology Agency, "Report of demonstration experiment evaluation committee on PCV spray effect", December 1981. (In Japanese)

### **23.12.5 Stand-By Liquid Control System**

[Ref-1] Chapter 6 of Preliminary Safety Report on Reactor Chemistry, GA91-9901-0041-00001  
Rev.B

[Ref-2] The Handbook of Chemistry Rev.2 basic edition II (The Chemical Society of Japan) (in  
Japanese)

### **23.12.6 Make-Up Water System and Condensate Storage Tank**

The references will be added in later GDA step as required.

### **23.12.7 Off-Gas System**

[Ref-1] Prospective Dose Modeling, GA91-9901-0026-00001 Rev.D

### **23.12.8 Flammability Risk Control System**

The references will be added in later GDA step as required.

### **23.12.9 Sampling and Monitoring System**

The references will be added in later GDA step as required.

### **23.12.10 Chemistry and Radiochemistry Limits and Conditions**

The references will be added in later GDA step as required.