Key Emerging Issues and Recent Progress Related to Plant Chemistry/Corrosion (PWRs, VVERs, CANDUs, PHWRs, and auxiliary systems)

Authors

Francis Nordmann
Beauchamp, France

Dewey Rochester
Charlotte, NC, USA

A.N.T. INTERNATIONAL®

Contents

1 Introduction

The NPC 2016 conference took place in Brighton (UK) 2-6 October 2016, organized by the Nuclear Institute. It was the 20th conference in the series of "Nuclear Power Plant Chemistry" that started in Bournemouth in 1977 and is now taking place every other year. The previous one, NPC 2014, was in Sapporo, Japan, while the next ones will be in San Francisco, USA in 2018 and French Riviera (Antibes) in 2020.

Over 243 participants from 21 countries attended this conference, a moderate participation in the history of these conferences. This location selection was close to the original one and appropriate considering that UK is the sole western country that ordered a new plant recently (2 EPR Units in Hinkley Point) financed by France and China, this last country having a very high number of units under construction.

The attendees from Europe included participants from the U.K. (75), France (30), Germany (4), Switzerland (9) plus others from Finland, Norway, Czech Republic and Belgium. There were attendees from Asia including Japan (31), China (9) and Korea. There were also attendees from America with the U.S.A. (22) and Canada (9).

Prior to the formal session special recognition was given to Dr. Jan Kysela, from the Czech Republic and formally an expert for ANT International, who passed away in December 2015.

The session for oral and poster papers were the following, after cancellation of several papers, particularly from Eastern Europe and Asia:

Table 1-1:   NPC 2016 Sessions and Papers

Subject Keynote	Oral Sessions		Poster Sessions	Total number of papers
	Number of session	Number of papers	Number of papers	
Keynote	1	3	1	4
PWR Primary Water Chemistry	3	12	28	40
Water Chemistry and Radiation	1	4	4	8
BWR Chemistry	2	8	16	24
Water Chemistry and Fuel	1	4	6	10
PWR Secondary Water Chemistry	3	11	18	29
Auxiliary Systems	2	6	12	18
Lifetime Management and Plant Ageing	2	6	5	11
High Temperature Reactors & Accident Management	1	4	4	8
Total	16	58	94	152

2 Primary water chemistry

2.1 General information

ANT presented a paper on the several aspects of primary and secondary chemistry [F. Nordmann et al., 2016]. The topics included crud mitigation, recycling of primary wastes and a risked information decision process on secondary chemistry contaminants.

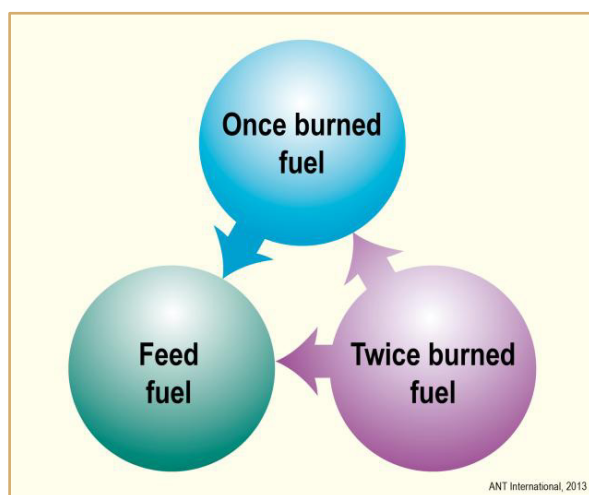Figure 2-1 describes the feedback loop for primary crud:

Figure 2-1: Schematic illustration of the CRUD movement from longer to shorter burned fuel assemblies within the core

These crud reduction techniques have been described in more detail in ANT papers and presentations. The second portion of the paper provided information on the recycling of evaporator distillate/tritium and its associated problems. Boric acid recycling was also described. These topics were covered in the ANT LCC11 seminar. The third portion of the paper dealt with secondary chemistry issues, see section 3.2).

2.2 Corrosion and activation products in RCS

Since late 90s, Ringhals AB has applied elevated pH regime in the PWR units 2 respectively 3 and since 2011 also in unit 4. Lowered plant dose rates from the primary circuits related to radio cobalt has been achieved. However, the dose rate decrease has not been fully understood. There was thus an interest to study explicitly how incorporation of activity in the form of radio cobalt depends on the water chemistry. In a paper at the NPC 2014-conference, results were presented concerning effect of Zn-dosage on Co-60 uptake.

The presented work [J. Öijerholm, et al., 2016 a] concerns exposure tests in an experimental circuit which is designed to simulate an entire reactor cycle. Uptake of Co-60 on tubular specimens of stainless steel, AISI 304L and Alloy 690 was studied at temperatures between 285°C and 325°C, respectively pH_{300} ranging from 6.9 to 7.6. The observed relation between slowly increasing exposure pH_T (at constant temperature) and Co-60 uptake was weak and contradicting. Dosage of Zn had a stronger influence, compared to altered pH_T, on uptake of Co-60. The uptake rate of Co-60 was higher on stainless steel compared to Alloy 690. Further, the Co-60 uptake on stainless steel appeared to be more sensitive to combined changes in pH_T and temperature compared to the uptake on Alloy 690. The influence of flow velocity was studied since the flow velocity in the experimental circuit is considerably lower compared to plant conditions. Increasing flow velocity by a factor of 150 increased the uptake rate of Co-60 considerably.

From the testing that was performed these conclusions were reached:

- pH was not observed to have any pronounced effect on uptake of Co-60 on Alloy 690 and stainless steel AISI 304L under simulated primary PWR conditions.

- There was no discernible general trend relating exposure pH and uptake rate of Co-60 on the studied specimen materials.

- The inhibiting effect Zn-dosage has on the uptake of Co-60 on Alloy 690 and stainless steel was not observed to be influenced by exposure pH.

- The uptake rate of Co-60 on AISI 304 was observed to be higher under simulated cold leg conditions, 285 °C and pH_{300} 7.1 compared to hot leg conditions, 325 °C and pH_{300} 7.4.

- On Alloy 690 uptake rate of Co-60 was not as strongly influenced by combined changes in $pH_{300°C}$ and exposure temperature as on AISI 304L.

- Increased flow velocity over the specimen surfaces resulted in a higher uptake rate of Co-60. However, the qualitative effect of exposure parameters such as Zn-dosage and $pH_{300°C}$ was not affected.

An EPRI Poster [J. McElrath, et al., 2016] reviewed a proposed model of activity incorporation into out of core piping surfaces.

Since extensive primary system piping surface activity and coolant Co-58 and Co-60 concentration data were available for the Ringhals 2, 3 and 4 pressurized water reactors, observations at these plants were employed in the evaluation. These plants also were of interest since zinc had not been injected to the primary system during the operating period that was considered, thereby simplifying model evaluation. Ringhals 2 and 3 were operating with Alloy 690 replacement steam generators and with the same pH_{300C} control program. Ringhals 4 was operating with the original Alloy 600 steam generators, and the pH_{300C} control program differed from that at Ringhals 2 and 3.

The proposed model assumes that the net incorporation rate of Co-58 and Co-60 into out-of-core oxide films on stainless steel surfaces is linearly proportional to the concentrations of soluble divalent species in the primary coolant. It also assumes that once the soluble species are incorporated into the spinel matrix, minimum release (<10%) to the coolant occurs during the shutdown transient. To test the proposed model, Co-58 incorporation rate constants were calculated for 26 cycles at Ringhals and six cycles at Beaver Valley. Co-60 incorporation rate constants were also calculated for most of these cycles.

Results are summarized as follows:

- Co-58 incorporation rates at Ringhals 2 and 3 are very similar, with both decreasing with time. The similarity in behaviour at Units 2 and 3 appears to support the premise that the incorporation rate was relatively independent of the coolant Co-58 concentration since steam generator materials, operating practices and the chemistry control programs were similar during the review period. The decrease with time could be viewed to be a result of long term filming of the Alloy 690 steam generators.

- Incorporation rates at Ringhals 4 were lower than those at Ringhals 2 and 3 during 2001 and 2002 but then increased with time. A difference in behaviour of Ringhals 2 and 3 compared to that at Unit 4 was expected due to the differences in steam generator materials and the pH_{300C} control program.

- Incorporation rates of Co-58 and Co-60 were reasonably similar at Ringhals 2 and 3 and Beaver Valley 1 and 2.

Although these results were encouraging, the incorporation rate varied almost linearly with the Ringhals 3 Co-58 concentration. The variability in the Co-60 incorporation rate remains a

concern although, as previously noted, estimation of a cycle by cycle incorporation rate for Co-60 is subject to a much greater error that that for Co-58.

Since it is also reasonable to assume that the incorporation rate is impacted by the concentration of particulates, consideration of a model attempting to empirically address the relative importance of the soluble and insoluble species should also be considered in the future.

This paper represents work in progress and the final model for cobalt incorporation has not been determined.

According to a Poster Paper from Finland [Buddas, et al., 2016] abnormal solid matter was observed in primary coolant samples at Loviisa Unit 2 (LO2) during the summer 2015. Also, some abnormal radioactivity results were detected in membrane filters of the primary coolant grab samples. The phenomenon about the radioactivity results had started in the beginning of 2015. In some of the samples, the activity of Cr-51 was ten times higher than normal.

The reason for the unconventional results was investigated. It was suspected that there might be problems with grab sampling, especially with flow rate. Also, crud release from the core was suspected. The observations didn't support either of these theories.

Some vibrations had been detected in one of the six primary coolant pumps (PCP) during the speculations of the sampling problems. About a fortnight before the yearly outage primary coolant pump was stopped due to too high vibrations. The pump was not started again and the plant continued running of at 80% thermal power until the outage.

The primary coolant pump was dismantled during outage and it was found that the thermal protection sleeve was damaged. Part of the material was grounded off and ended into the primary coolant causing the abnormal solid matter observations.

On 10 August were both total and soluble metals determined from primary coolant (TV04, reactor inlet water) to identify in which form the metals are. Analyses results showed that the metals were mainly in particle form. The results are presented in Table 2-1.

Table 2-1: The metal concentrations of the primary coolant (LO2 TV04) on 10 August 2015 [Buddas, et al., 2016]

Parameter	Results [ppb]	Normal value [ppb]
Total Fe	26	2 - 3
Soluble Fe	1.0	2 - 3
Total Ni	4.1	0.1
Soluble Ni	0.1	0.1
Total Mn	0.3	< 0.1
Soluble Mn	0.05	-

The reason for the abnormal results was investigated from various point of views. The phenomenon was first speculated to be due to the crud from the sample lines because the results' variation. The way how to open the sample valve was harmonised in the laboratory. The flow rate of the sample line was checked and it was twice higher than it should be. But the solid matter and radiochemistry results varied still after adjusting the flow rate.

The reactor and fuel engineers were asked to check if there were anomalous in the parameters of the core because of the slightly increased Nb-95, Zr-95 and Hf-181 activities. But there were no detected incidents. But the engineers thought that the origin of the crud could be the absorbators that have deposits on them. The deposits were formed after primary circuit decontamination in 1994. The deposits on the absorbators contains 60 - 90% iron, 2 - 6% nickel, 1 000 - 6 000 µg/g

manganese and some smaller amount of other substances like Nb and Hf. No reason could be found to explain why the deposits would have decomposed. The deposits have been on the absorbators already for 20 years.

The phenomenon was new at Loviisa NPP. It wasn't even imagined that such a huge amount of material could ground from a PCP without identifying it by equipment reliability measurements. Afterwards, of course, one could say that all the indications: solid matter, total iron and Cr-51 pointed out to that. At present total Cr is analysed among other corrosion products. Also, more attention is put to the following of the Cr-51 results. If there are any deviating laboratory results, or anomaly in other equipment reliability measurement parameters, e.g. PCP vibrations, persons that are involved in primary coolant pump monitoring will meet to evaluate the situation.

This paper will be of interest to any plant that has experienced a similar issue.

J. McGrady from the University of Manchester presented "Characterisation and Behaviour of Particulate Material in PWR Primary Coolant", [J. McGrady, et al., 2016]. Below is the abstract and their conclusions.

The corrosion of primary circuit structural materials in a PWR is the precursor to the formation of particulate corrosion products in primary coolant. These corrosion products can cause several issues that affect the safe operation and performance of a nuclear power plant, including: an increased radiation field, reduced hydrodynamic performance, reduced heat transfer efficiency, and the axial offset anomaly (AOA). To minimise these issues, the issue of corrosion products formation needs to be more comprehensively understood at operating conditions. In this work, corrosion products were formed under simulated PWR conditions, their physical attributes were characterised, and the processes that drive the deposition of the corrosion products in accelerated flow regions were investigated.

A refreshed autoclave loop with a control system capable of accurately controlling and monitoring online the water chemistry was used to investigate the effect of water chemistry on corrosion product formation and deposition. Corrosion products formed in simulated coolant were analysed by an ex-situ ultra-filtration technique to isolate particulates and ICP-MS was employed to monitor the solubility of dissolved metal ions. Further, a flow cell containing a stainless steel disc with a central micro-orifice was used in the recirculating autoclave system to analyse deposition processes under accelerated flow conditions. All corrosion products were analysed by complementary techniques including SEM-EDS, laser confocal microscopy and Raman spectroscopy. The effect of water chemistry (Fe^{2+}, H_2) and material on the corrosion product deposition was investigated and discussed in this paper.

- A simple set-up has been developed that enables investigation into the preferential deposition of CRUD in accelerated flow regions under PWR conditions. Simulated PWR coolant chemistry was accurately controlled to analyse the effect of water chemistry on CRUD deposition.

- Deposited oxides on the discs were identified as magnetite, Fe_3O_4, and ultra-filtrated species from solution were identified as lepidocrocite, γ-FeOOH, due to the dissolution of the spinels upon cooling of the water.

3 Secondary water chemistry

3.1 General information

SWAN Instruments presented Paper #127 [Gath et al., 2016] which was a marketing paper concerning the use of electro-deionization device (EDI) to remove ammonia and other amines from the secondary coolant prior to passing it through a cation resin column to measure conductivity.

The use of EDI results in a much longer cation resin life without replacement. The paper also claims that conductivity after cation exchange (CACE, a.k.a. cation conductivity) is lower with the use of EDI. The paper also discusses the use of EDI prior to the cation column in ion chromatography.

The authors concluded that using EDI instead of the passive cation exchange column gives less contributions from the resin to the CACE reading, resulting in lower and more correct CACE values. No cation leakage through the EDI module nor chloride loss could be detected, making the EDI technique suitable for the use in CACE monitors. As the impact of the resin on the measurement is minimized, temperature dependent anion leakage and the flow dependency of the measurements are also minimized, leading to well reproducible measurements.

The paper gives some good background on cation conductivity measurements. The EDI system seems to work effectively but a cost-benefit analysis should be done comparing the costs of regenerating/replacing the cation resin vs. the purchase of an EDI.

3.2 Chemical additives options and strategies

Table 3-1 summarizes the practical aspects for chemistry regimes as discussed within ANT-I [Nordmann et al, 2016].

Table 3-1:   Overall Rationale for Secondary System Treatment Selection

Cu[a]	CPP[b]	Other	Rationale	Treatment
Yes	Yes or No		If expected plant life remains significant, consider copper alloys elimination	In this case, see no Cu
Yes	Yes or No		With Cu, amine at low $pH_{25°C}$ of 9.2 ($\pm$ 0.1) is mandatory. Higher pH incompatible with Cu alloys and lower pH insufficient for FAC and corrosion products transport to SG.	Amine (morpholine or ETA) at $pH_{25°C}$ of 9.2 ($\pm$ 0.1)
No	Yes		Consider using it only temporarily during start up and if any pollution (e.g. condenser leak). Most part of time, put in by-pass mode, ready to be used	If in by pass mode, see no CPP case
No	Yes		If in permanent operation full time, amine treatment is mandatory for limited molar concentration and thus acceptable regeneration frequency at a sufficient pH_T. ETA is preferable due to lower molar concentration than morpholine	Amine at moderate $pH_{25°C}$ of $\approx$ 9.4-9.5. ETA is the best
No	No		Best situation, more and more frequent, for achieving a sufficient pH_T and thus low FAC and corrosion products transport to SG. Select the highest pH compatible with SGBD operation and wastes releases to the environment.	H-AVT (NH_3) at $pH_{25°C}$ of 9.8 to 10 or amine at $pH_{25°C}$ > 9.5
No	No	Waste	If any restriction for nitrogen compounds on liquid wastes releases into the environment, ETA is the best according to lower molar concentration. Consider recycling Condenser Air Removal system effluents after treatment (for anions elimination) if necessary. Consider operating SGBD after exhaustion of cationic IER by the reagent and no IER regeneration	ETA at compatible $pH_{25°C}$ (e.g. $\approx$ 9.4-9.6) Morpholine if better results with cationic IER of SGBD saturated
No	No	Resistant SG tubing 800, 690, or 18-10Ti	With Alloys 800, 690 or 18-10, consider operation with less restrictive SGBD specification that what is applied with Alloy 600MA. Thus, it may be possible to operate with cationic IER of SGBD saturated and without any regeneration, or with only regeneration of cationic IER but not of mixed bed. This eliminates risk of SG contamination by chemicals during regeneration or by resin fines.	Amine at $pH_{25°C}$ > 9.5. ETA or morpholine, depending on performances of IER at SGBD
[a] Cu = Presence of copper alloys. [b] CPP = Presence of Condensate Polishing plant					

A risk informed approach should be taken to the selection of secondary operating conditions, that is: a balance between operating costs vs. materials protection (especially SG tubing) must be optimized to ensure safe and reliable operation.

3.2.1   Amines

As stated by ANT International expert in its reports as well as in published papers [Nordmann 2006, Nordmann 2008, Nordmann 2010, and Nordmann 2012], EPRI confirms that it is of high importance to focus on management of corrosion products that impact Steam Generator (SG) performance with potential loss of heat transfer, concentration of impurities in deposits where they may induce corrosion, and need for SG cleaning. The secondary treatment, to minimize such corrosion products generation as well as mitigating Flow Accelerated Corrosion (FAC) of carbon steel either requires the use of H-AVT (ammonia at a pH close to 10) or the use of amine to reach a higher pH_T while keeping a reasonable concentration of reagent, that is important for Ion Exchange Resins (IER) duration, and for acceptable liquid and solid wastes releases into the environment.

Consequently, most of French PWR units started to use morpholine treatment as early as 1983, while based on EPRI recommendation, amines have been widely used later in the USA, in 1997

[Wells, 2016 a]. The update of the use of amines in the secondary system, Figure 3-1, shows that Ethanolamine (ETA) or other amines or mixing of amines is now applied in all the US PWR units.
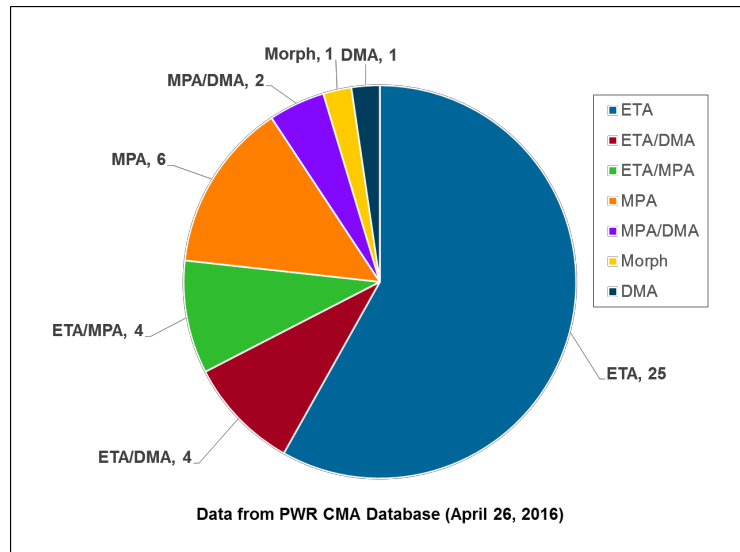

Figure 3-1   Current amine use in US PWR secondary systems [Wells et al., 2016 a]

A Russian study used a model describing the distribution of concentrations of ethanolamine and ammonia, corrosion and mass transfer of corrosion products in the secondary system of VVER-1200 units. A verification of the models has been made by using the results of chemical analyses and the concentrations of iron corrosion products in feedwater on various VVER units depending on $pH_{25°C}$ [Kritsky, et al., 2016].

To raise pHt, especially in two-phase flows regions, on new VVER units without copper alloys in the secondary circuit, ammonia–ethanolamine treatment has been selected. Various curves have been established to show (i) on left part of Figure 3-2 the dependence of corrosion rate of carbon steel on $pH_{25°C}$, for various temperatures and (ii) on right part of Figure 3-2 the evolution of Fe^{2+} concentration in the final feedwater of Kalinin VVE(Russia).

4   Auxiliary systems

Typically, the corrosion control in Closed Cooling Water (CCW) system is achieved by adding one or more corrosion inhibitors such as chromates, nitrites, molybdates, hydrazine, silicates and phosphates. China usually uses chromates, nitrites, and phosphates as corrosion inhibitors in CCW systems where the piping consists of carbon steel and heat exchanger tubing consists of copper alloy (or some corrosion resistant alloy such as stainless steel or titanium alloy). However, these inhibitors, when used separately, may cause problems such as environmental discharge issues, mammalian toxicity, microbiological growth due to nutrient ingredient, and high costs. A Chinese Institute, in connection with University, investigated molybdates and tolytriazole (TTA), as alternative inhibitors for carbon steel (SA106GrB / ASTM A106/A106M) and brass using potential dynamic polarization (Zn, 38.81% and Cu) [Bao Yi-Chen et al., 2016].

For solutions containing $NaNO_2$, Na_2MoO_4 and TTA-Na at 35 °C, the results showed a synergistic effect between Na_2MoO_4 and $NaNO_2$ acting as passivating anodic inhibitors on carbon steel, with an inhibition efficiency up to 98.4% in pH 10 solution with an optimal ratio of 3.2: 1 (as ppm MoO_4^{2-}: ppm NO_2^-) while this compound has little benefit on corrosion inhibition of brass without TTA. When TTA was added into the solution, the chemisorption between TTA molecules and brass surface could increase the inhibition for both anodic and cathodic reactions and inhibition efficiency could reach 99.5% with an optimal ratio of 3.2: 1: 0.7 (as ppm MoO_4^{2-}: ppm NO_2^-: ppm TTA). The influence of Cl^- (10 ppm) was also studied. The results show that Na_2MoO_4+ $NaNO_2$ could raise the breakdown potential from -581 mVSCE to 747 mVSCE with a good inhibition of pitting. But the addition of TTA-Na seems to have a negative effect on corrosion inhibition probably because TTA covering layer might impede the inflow of anions so that MoO_4^2 or NO_2^- could not react with metals adequately. For brass, the breakdown potential moved from 0.0 mV_{SCE} to 1208 mV_{SCE} but no remarkable benefit on inhibition efficiency was observed since halide may facilitate adsorption of organic inhibitors, due to the competitive adsorption between Cl^- and MoO_4^{2-}/ NO_2^- [Bao Yi-Chen et al., 2016].

Palladium resin (ion exchange resin either doped with Pd or coated with Pd) has been used in the Stator Cooling Water Circuit (SCWS) in several generator units operated by EDF Energy Nuclear Generation Ltd to maintain low oxygen concentrations. C. Atkinson, Boilers, Chemistry and Plant Performance Branch, EDF Energy Nuclear Generation, UK, presented information on the use of Pd resins [Atkinson et al., 2016]. The Pd-resin has been shown to substantially reduce the dissolved oxygen concentration when sufficient dissolved hydrogen is present thereby reducing the potential for corrosion within the stator circuit. In some instances, the Pd-resin has been known to operate beyond its recommended temperature range and this has potentially led to operational challenges. These primarily relate to the stability of the Pd-resin itself and its subsequent impact upon other parts of the stator circuit. It is believed to be the cause of difficulties in controlling the pH, the source of many impurities and may have created latent issues relating to the stator circuit and its purification system in that the problem has persisted after a chemical clean of the stator.

The background behind the decision to adopt Pd-resin as a means of controlling the oxygen concentration, the operational benefits of using Pd-resin and the subsequent challenges and drawbacks encountered since its introduction is discussed.

Within the EDF Energy fleet there are various configurations of the SCWS and its purification system. The purification system forms part of a bypass circuit and can be operated as a separate anion and cation column or as a mixed bed and cation column. The purification system is operated intermittently to remove impurities. Typically, the resin used is Dow IRN 77 (cation) and Dow IRN 78 (anion).

Most EDF Energy's NPP operate their SCWS with a low oxygen-elevated pH regime, which is defined as a dissolved oxygen content less than 50 µg.kg-1 and a target pH of 8.5 – 8.7. There is an option of operating at a high oxygen-elevated pH regime but generally the low oxygen regime is preferred because it is easier to maintain. Switching between the two regimes is discouraged [Atkinson et al., 2016]. Table 4-1 shows the different parameters for the two systems.

Table 4-1:   Target parameters for various stator regimes [Atkinson et al., 2016]

Control Parameter	Low Oxygen	High Oxygen
Conductivity (μS.cm^{-1})	0.1 – 3.0	0.1 – 3.0
pH	8.5 – 8.7	8.5 – 8.7
Dissolved Oxygen (μg.kg^{-1})	< 10	> 4000
Diagnostic Parameter		
Copper (μg.kg^{-1})	< 5	< 5

Control of the dissolved oxygen concentration to less than 50 µg/kg has historically proven difficult on some units, with a membrane degasser proving ineffective. Alternatives were therefore investigated that would facilitate the control of the dissolved oxygen concentration.

Approximately 5 L of Pd-resin was installed in the first unit as a trial in November 2008 and a second in February 2009. The resin was enclosed in a fabric bag in front of the anion column, giving a bed depth of approximately 200 mm. The dissolved oxygen concentration immediately reduced the palladium resin, with one unit showing an immediate reduction to below the target dissolved oxygen concentration and the other unit trending downwards to below the target value of 50 µg/kg as shown on Figure 4-1.
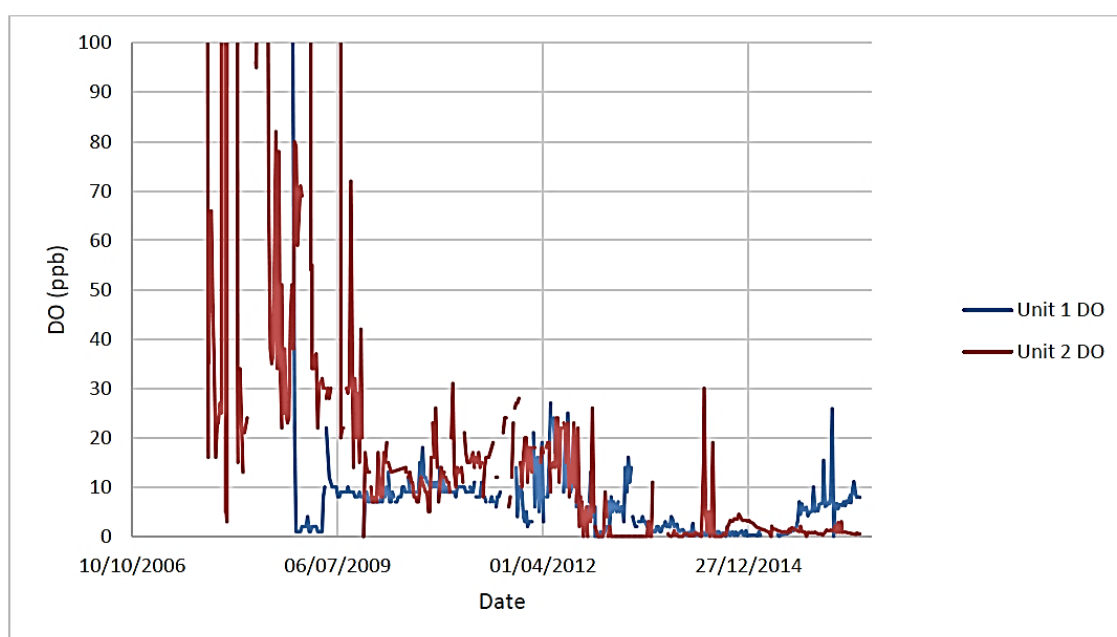
Figure 4-1   Dissolved oxygen (DO) concentration following installation of Pd-resin [Atkinson, et al., 2016]

However, in 2015 the original trial station reported difficulties controlling the pH of the stator circuit of their French PWR units. Analysis using ion chromatography revealed the presence of methylamine (MMA), trimethylamine (TMA) and additional ionic species also thought to be an amine. These species were estimated to be present at a significant concentration, greater than 1 mg/L.

After thorough investigation, the conclusions were [Atkinson, et al., 2016]:

- There was a significant amount of copper transport occurring within the SCWS
- Palladium was still present within the SCWS. SCWS water samples were analysed for Pd via ICP-MS but did not show detectable Pd (< 0.01 µg/L)
- Degradation of the ion exchange resins may be occurring despite being in service for three months. This was also supported by the continuing increase in amines.

There is conflicting evidence about the long-term consequences of operating with Pd-doped resin however [Atkinson et al., 2016]:

- The original trial units are suffering from long-term operational issues (difficulty controlling the pH and conductivity, increased copper transport around the circuit) because of the release of amines into the circuit.
- Two units are understood to have had negligible issues while operating with Pd resin.
- An attempt to utilise Pd-resin on two further units were aborted at an early stage due to difficulty controlling the pH.

This paper will be of interest to those utilities considering the use of Pd-doped resin or those already using it with similar issues.

Turbidity has been observed in spent fuel Pool (SFP) and reactor pools (RP) in France and other countries. Due to an increase in the last few years in significant cases, which have led to the loss of production, EDF launched an international Operating Experience Feedback in its 58 French PWR as well as many other NPP (Brazil, Canada, China, Japan, South Africa, South Korea, Spain, Sweden, UK and North America), from which many interesting results have been gathered [Trebilco, et al., 2016]. In France, 85%of turbidity problems occurred in RP and 15% in SFP. On the opposite, in other countries 65 % of the events affected the SFP 65% versus only 35% in the RP, as shown on Figure 4-2.
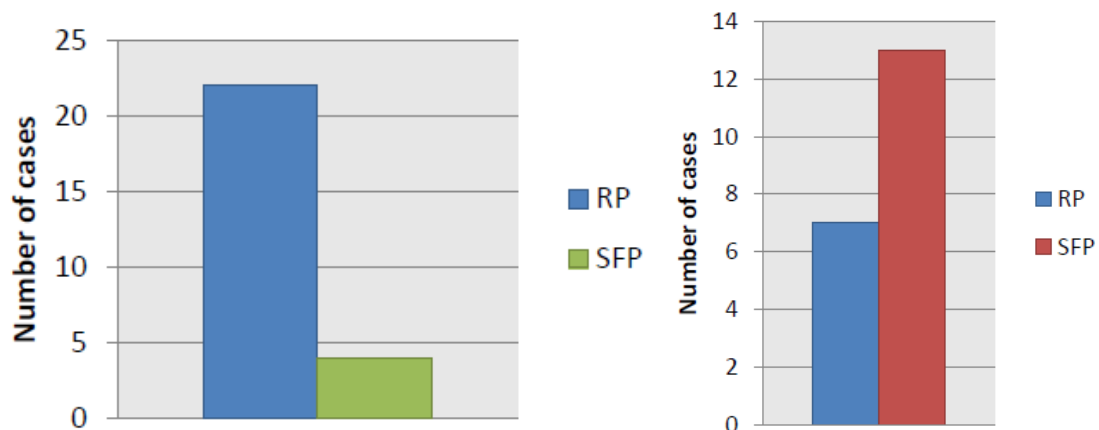
Figure 4-2   Which pool was affected) where RP = Reactor Pool); SFP = spent fuel Pool in units in France ((left) and other countries (right) [Trebilco et al., 2016].

The consequences of these turbidity events illustrated on Figure 4-3 are not only affecting production loss but also dose increase and the inability of non-destructive testing (NDT) to be carried out that will also affect the critical path and therefore the plant availability [Trebilco et al., 2016].

5   Materials corrosion

5.1   Stainless Steels and various alloys

Several results of comparison of corrosion resistance of various alloys in the RCS with LiOH or KOH are given in section 2.5.2.

A Chinese laboratory study looked at the influence of crevice geometry on crevice corrosion behaviour of AISI 304 Stainless Steel in 290°C pure water containing different Dissolved Oxygen (DO) concentration using a crevice corrosion device. This showed that crevice geometry and DO can affect the crevice corrosion characteristics of 304 in high temperature water.

Since several major components of a reactor internals and spent fuel pools are made of stainless steels, there is a realistic concern for Japanese NPP about localized corrosion due to chloride contained in sea water. Experiments on critical potentials both for initiation of crevice corrosion and re-passivation of a corroding crevice in chloride containing solution with stainless steels 304L and 316L stainless steels have been evaluated, by using potentiostatic immersion as long as 30 days. Although there was almost no difference between the two alloys in the critical potential for initiation of crevice corrosion, as shown on Figure 5-1, non-negligible difference was found in the critical potential for repassivation of corroding crevice Figure 5-2. For 316L stainless steel, critical potential for repassivation was nobler than that for initiation. This behaviour was considered due to the effect of molybdate ion originated from alloyed Mo, which was condensed in a crevice as crevice corrosion was developed [Watanabe et al., 2016].
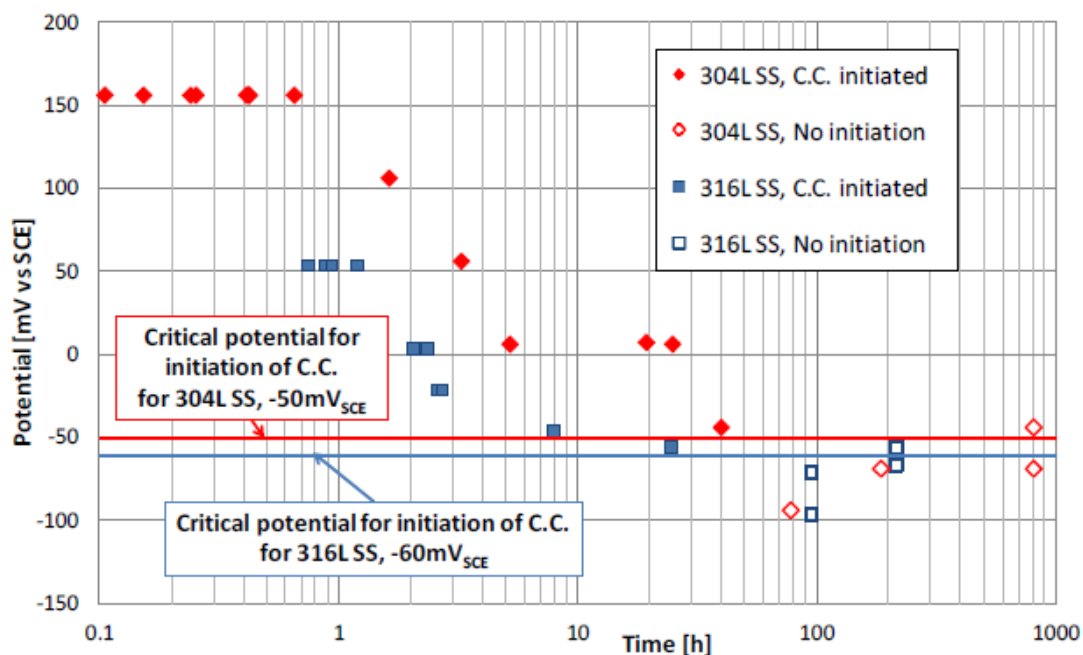

Figure 5-1   Summary of initiation experiments of crevice corrosion for AISI 304L and 316L stainless steels in 1000ppm [Cl-] neutral solution at 50˚C [Watanabe et al., 2016].
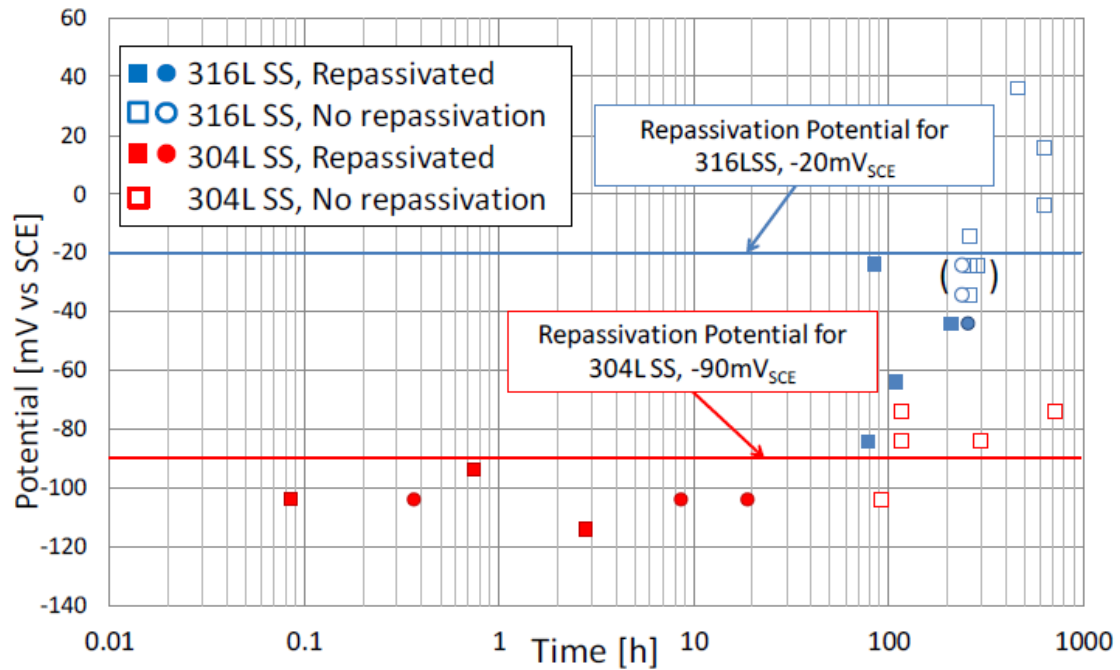
Figure 5-2   Summary of repassivation experiments of corroding crevice for AISI 304L and 316L stainless steels in 1000ppm [Cl-] neutral solution at 50°C [Watanabe et al., 2016].

There was relatively clear difference in crevice corrosion morphology depending on testing potential found for the 316L initiation test specimens. For the initiation test specimens tested above the repassivation potential, corrosion grooves were developed and extended to the crevice edge as shown in Figure 5-3.

Figure 5-3   Corrosion morphologies in crevice found in the initiation experiments on AISI 316 stainless steels. Corrosion grooves were developed above the passivation potential in contrast to corrosion pits formed below the repassivation potential [Watanabe et al., 2016].

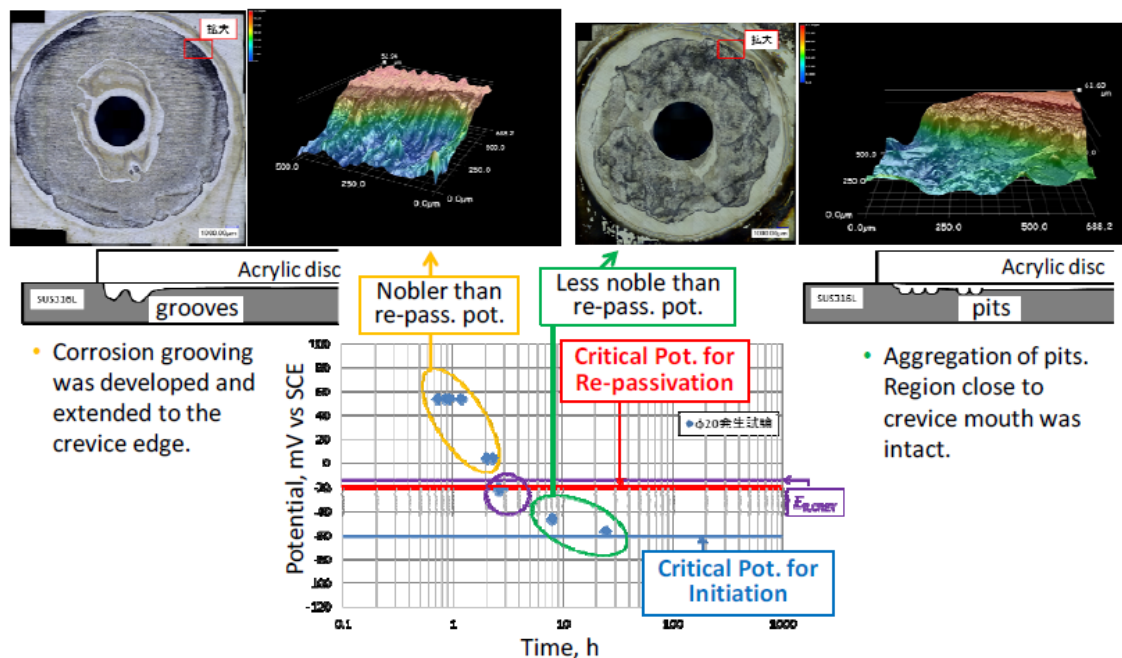An Indian study in Laboratory looked at the role of magnesium ions in the passivation behaviour of Alloy Incoloy 800, which is used in Pressurized Heavy Water Reactors (PHWRs). Polycrystalline porous nickel ferrite was found to form on the passivated Incoloy 800 surfaces. The overall resistance of magnesium incorporated oxide film increased, pointing out the corrosion process modification by incorporated magnesium ions.

PWR of several countries use amines to control pH in the secondary system for minimizing corrosion of carbon steel. However, some turbine vendors, especially in Germany, do not recommend the use of such amines due to the increased organic acids concentrations measured by cation conductivity in steam that may pose a corrosion risk to turbines. Consequently, EPRI has coordinated an expert panel, including utility members, turbine vendors, and EPRI representatives from both the fossil and nuclear sectors to address the potential corrosion risk from organic acids. The panel identified testing needed to evaluate the effect, if any, of acetate and formate on the pitting susceptibility of steam turbine materials.

5.2 Steam Generator (SG) Tubing

An operating experience feedback of corrosion of SG tubing in Bruce A & B in Canada has been studied. The secondary side corrosion of Alloy Inconel 600 mill annealed (I600 MA) with stress relieved tubing in both A and B stations, is different from unit to unit. Within the well-known influencing parameters, material susceptibility, stress level and chemical environment, it is concluded that the control of water chemistry is the most important factor to tubing performance with respect to Stress Corrosion Cracking (SCC) initiation. Improved control of local and bulk chemistry environments will help plants to delay the onset of tubing degradation [Lu and Roberts, 2016]. A previous large study in many EDF units had shown that the detrimental factors are the material characteristics (large difference in corrosion from heat to heat) and the alkalinity of the chemical environment, with much more corrosion in units cooled with alkaline forming water than in units cooled by sea water which is producing a small acidity in the SG [Nordmann and Stutzmann 1996].

As reported in the last LCC reports (LCC10 and LCC11), an important issue of SG tubing corrosion is coming from deposits on the top of tubesheet, inducing the denting phenomenon and SCC of SG tubes, as this occurred in Spanish units with Alloy Incoloy 800. This is of importance since it affected resistant SG tubing alloy and may ultimately concern many new SG (either from recent units or replaced SGs in older units). SG have been replaced in Almaráz and Asco Units 1 and 2 between 1995 and 1997, then denting was detected in 2006 in Almaráz SG-3 of Unit 2, followed by other SGs from Almaráz and Asco. Consequently, the CIEMAT laboratory in Spain characterized the sludge microstructure and how to better avoid and eliminate this sludge [Diego and Merino, 2016].

After sub-samples separation, M (magnetite layered), C (collars) and F (flakes) pieces were identified visually to characterize macroscopic features such as size, shape and colour. Figure 5-4 shows macroscopic photographs of selected Almaráz deposit sub-samples after one and three injections of Film Forming Amine (FFA). Typical magnetite pieces were present as small "gravel", generally on the order of a few millimetres of length. The colours of these pieces were grey with areas of orange tone and showed geometries and curvature compatible with the triangular shape of the space between tubes in SG tubesheet, Figure 5-5.

6 Safety - Wastes and Environmental Issues

6.1 Safety Aspects

To focus on Safety aspects in chemistry, the first keynote paper was related to Regulating Chemistry for New Nuclear Power Stations in Great Britain [Glover, 2016]. It has been explained that adequate consideration of chemistry in the safety case for new nuclear reactors is important to the demonstration that they are safe to build and operate. Chemistry directly influences several hazards, relating to reactivity, pressure boundary integrity, fuel and core component integrity, radioactive waste generation and radiological doses to workers and the public. Chemistry phenomena can also affect the progression and consequences of accidents. Safety is of great concern in Great Britain with many old units that are reaching their end of life, whilst several other units are expected to be built: 2 EPR units (PWR of European design) at Hinkley Point C that should start in the mid 2020's, 2 other EPR at Sizewell C, 3 AP1000 (PWR of Westinghouse design) at Moorside in the late 2025, 1 Huanlong (PWR of Chinese design) at Bradwell, 2 ABWR at Wylfa also in the mid 2020's and 2 other ABWR at Oldbury B. The safety assessment concentrates on the chemistry related aspects of:

- The safety case for the justification, implications and control of coolant chemistry during all modes of operation.

- Those features of the design, material choices or chemistry controls which reduce radioactivity As Low As Reasonable Practicable (ALARP).

- The main secondary or auxiliary circuit systems which control or are influenced by chemistry.

- Those engineered systems which allow control, monitoring or changes to the plant chemistry.

- The storage of nuclear fuel within ponds (pools), including the effects of water chemistry.

- Those systems which mitigate the release of radioactivity to the environment in either the liquid or gaseous form.

- Design basis and beyond design basis accidents, including the production, release and control of hydrogen and fission product nuclides.

- The arrangements for moving the safety case to an operating regime, including the derivation of suitable limits and conditions and the arrangements for specifying plant chemistry [Glover et al., 2016].

All nuclear power plants (NPPs) in Japan were shut down because of the Fukushima-Daiichi accident. Now only two PWRs are operating to meet the new regulation requirement, which requests for the plant utilities to secure sufficient safety margins against the defence in depth level 4 under miscellaneous internal and external conditions as well as much higher reliabilities on plant operation. It takes a long time to get permission for restart the plants with scheduled shutdown due to review for checking the conformity to New Nuclear Regulation Authority Requirement and newly required pre-service inspections. It took about 2 years after all plants shut-down to a PWR was officially started up, as shown in Figure 6-1. Now more than 10 PWRs have submitted the operation proposals and most of them almost finished reviewing and wait for getting the permission. In 2017, most of them should re-start [Katsumura et al., 2016].
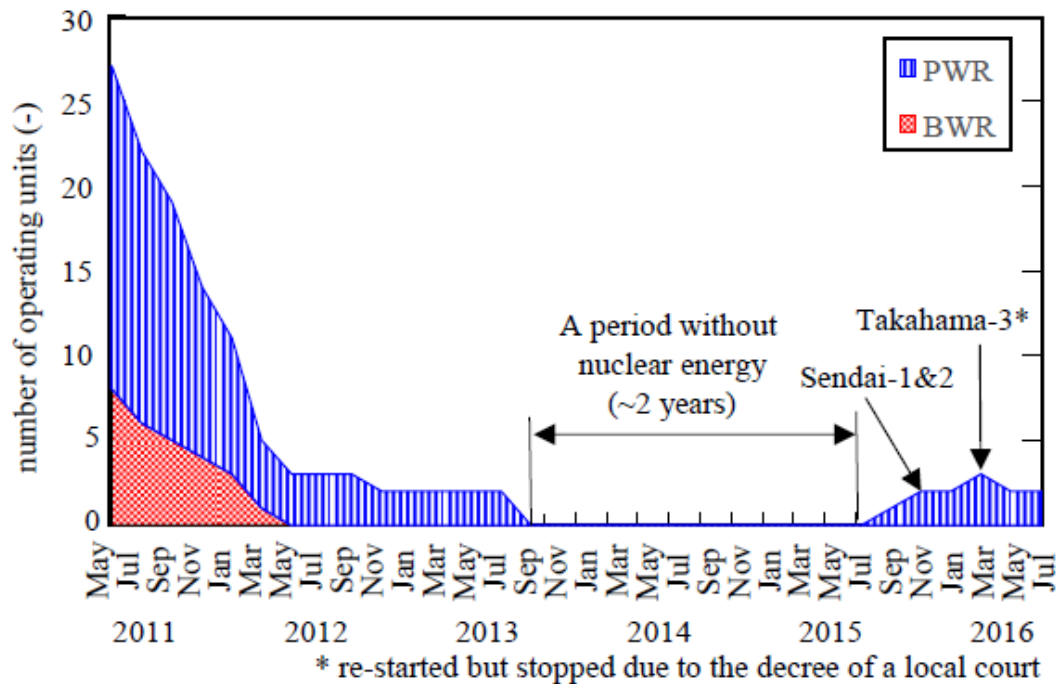
Figure 6-1   Evolution of units in operation in Japan, before, during and after Fukushima accident [Katsumura et al., 2016]

The Nuclear Regulation Authority of Japan amended the regulation requirement which contained countermeasures against severe accident illustrated in Figure 6-2. In the requirement, the previous ones were reinforced with much severer criteria and some more items were added to prevent core and primary containment vessel damages [Katsumura, 2016].
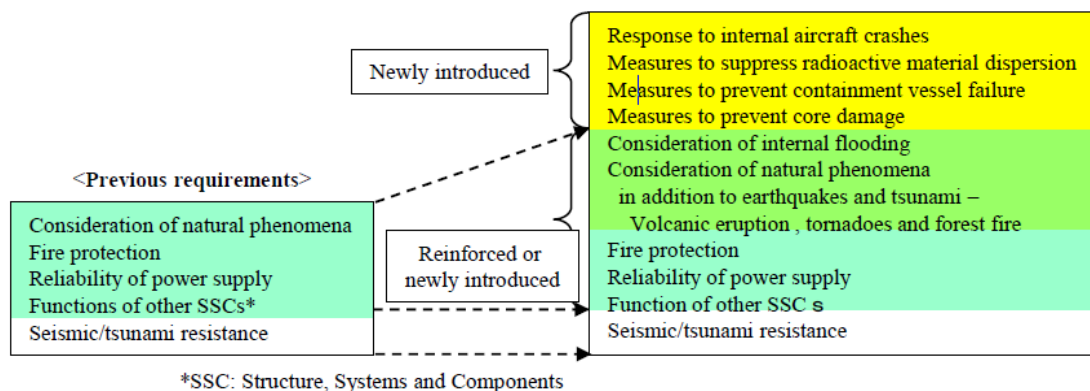

Figure 6-2   New regulatory requirements in Japan [Katsumura et al., 2016]

The technical support of the French Regulator made a presentation on the relation between the chemistry of the secondary system and safety aspects of PWRs with several aspects that should be argued.

A poster paper explained the role of the Canadian Nuclear Safety Commission (CNSC) as the federal regulator of nuclear industry in Canada. CNSC supports research to gain objective scientific knowledge to provide the foundation for clear legislation, relevant regulations and reliable evidence-based decision making. CNSC has sponsored several research activities to promote science for making Regulator decision [Kameswaran and Yacyshyn, 2016]. It is interesting to note the diversity of organisations, both in Canada and internationally, receiving

funds from CNSC for research in the private sector, academic institutions, and governmental/
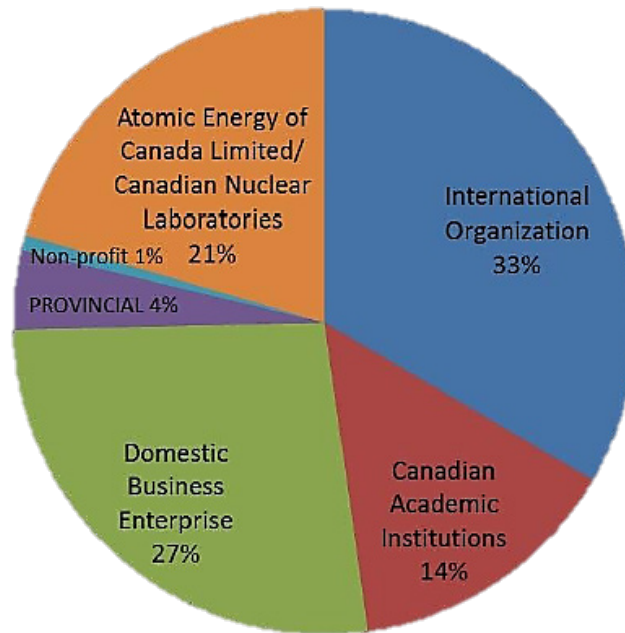non-governmental organizations, as shown on Figure 6-3.

Figure 6-3   Percentage of CNSC projects by research organization [Kameswaran and Yacyshyn, 2016]

Tigeras discussed the role of chemistry and radiochemistry in the post-accident monitoring in
Flamanville 3 and Hickley Point C in the design capabilities [Tigeras et al., 2016 b].

The Fukushima event in March 2011 has led to the re-evaluation of several domains related to
accident progression and post-accident monitoring for operating plants and new reactors. EDF
has performed an exhaustive assessment into the role of chemistry and radiochemistry for
Flamanville 3 (FA3-EPR) and Hinkley Point C (HPC-EPR), under accident and post-accident
conditions, to decide on the most suitable design for chemical and radiochemical monitoring and
control.

Depending on the requirements and recommendations associated with specific chemical and
radiochemical parameters, the monitoring capabilities have been selected based on:

- International standards and guidelines

- Severe accident strategies, fault operating procedures and safety studies.

- The specific design and operation of FA3 and HPC.

The main conclusions are [Tigeras et al., 2016 b]:

- A limited number of key, online parameters are required for the management of
  accident situations.

- Chemical and radiochemical sampling is not essential to bring the plant back to a safe
  state.

- In the short term, only online parameters (temperature, pressure, water level, neutron
  flux, containment and steam generator activity) are required to manage the event.

- In the long term, certain chemical and radiochemical sampling can provide useful information to aid and support plant recovery, effluent management and public communications.

(Note: The co-author (Rochester) of this ANT report notes that a similar study was performed in the U.S. more than sixteen years with much the same conclusions.)

This paper may be useful for plants that have not or are considering the removal or upgrades of any chemical or radiochemical post-accident monitoring systems.

The two Wylfa Magnox reactors in UK began power operation in 1971 and generation finally ceased in December 2015. They represented the ultimate design in the Magnox series of nuclear reactors and were built with spherical pre-stressed concrete pressure vessels with integral "once through" carbon steel boilers fitted into the space between the cylinder of the core and the sphere of the pressure vessel. Over the four decades of operation, several potentially life limiting issues related to the boilers arose: (1) Fretting (2), FAC (3), Crevice corrosion and subsequent FAC (4) Environmentally assisted cracking. All the issues threatened to shorten the generating life of Wylfa. The fact that these problems were overcome is testament to the hard work and dedication of the many teams and disciplines involved [Raffel and Garbett, 2016].

Sizewell B power station has recently started to transfer Spent Fuel Assemblies (SFAs) from the Fuel Storage Pond (FSP) to on-site dry storage, known as the Dry Fuel Store (DFS). Casks known as Multi-Purpose Canisters (MPCs) are submerged and loaded with 24 SFAs. The MPCs are drained of water containing boric acid, which is replaced with a pressurised helium environment [Davis et al., 2016].

A Gas Sampling & Analysis Trolley (GS&A) was built to test the gases inside the MPC. The testing will satisfy two key elements of the DFS safety case: 1) the Helium atmosphere inside the MPC is sufficiently pure to ensure minimal risk of corrosion of both the SFAs and the inside of the MPC; and 2) ensure the fission product barrier on the SFAs has not been breached. The gases that are sampled by the GS&A are argon, water vapour, nitrogen, oxygen, hydrogen, helium and krypton. The first five are potential external contaminants, whereas krypton analysis is used to confirm the absence of failed fuel.

The GS&A is connected to the Forced Helium Dehydrator (FHD) via two inlets and two outputs. The Helium Purge Line is used to ensure a clean helium environment for calibration and standardisation of the GS&A's instruments, as well as removing any impurities that may be present in the GS&A internals. The gas flow within the GS&A internals is controlled through a series of flow control valves, flow meters and diverter valves to avoid chemical and radiological contamination and saturation of sensors. This purge helium is tested with the mass spectrometer to ensure it has >99% purity and that it is sufficiently dry, using a dew point meter, before it is returned to the FHD in the FHD Return Line. Sample cylinders containing known concentrations of test gases are stored within the trolley itself and are also used to calibrate the oxygen analyser and the mass spectrometer for hydrogen, nitrogen and oxygen.

Once set-up of the GS&A is complete, it is ready for analysis of the MPC via the FHD Sample Line. The gas in the MPC is tested for the presence of argon, hydrogen, krypton, nitrogen, oxygen and moisture, as well as the purity of helium. Most of the gases are analysed using the in-built mass spectrometer but the GS&A also has moisture and oxygen analysers. A sample cylinder and Marinelli beaker can also be connected to the trolley to carry samples off for additional testing, see Figure 6-4 [Davis et al., 2016].

7 Plant start-up and shut-down

7.1 Operating process

C. Marks, Dominion Engineering (DEI), presented a study [Marks, et. al., 2016 b] of the use of reactor coolant pumps (RCP) during shutdown and the forced oxidation. The objective was to determine whether any specific RCP run strategy resulted in lower out of core dose rates.

The following RCP run strategies were evaluated:

Strategy 1:   Operate at least one RCP during forced oxidation and clean-up

Strategy 2:   Secure RCPs before forced oxidation, clean-up full system volume

Strategy 3:   Secure RCPs and reduce system volume before forced oxidation

During shutdown, a significant release of corrosion products from the core occurs. A much less significant release may occur from the deposits on out-of-core surfaces, such as the SG tubes and reactor coolant system (RCS) piping. Corrosion product release occurs because of a number of factors including the decrease in the primary system temperature, a decrease in the pH, and an increase in the oxidation potential (i.e., the transitions from alkaline reducing to acid reducing conditions then to acid oxidizing conditions through forced oxidation), all of which act to increase the solubility of nickel.

Based on the available data set, no clear effect of shutdown strategy (Strategy 1, 2, or 3) on out-of-core radiation fields could be identified, which may indicate that parameters not considered in this analysis have a stronger influence.

Regarding the effect of RCP run time (i.e., time of RCP operation after forced oxidation) on Strategy 1 shutdown performance, the following observations were made concerning the metrics that may be affected by RCP run time [Marks, et. al., 2016 b]:

- Longer RCP run times generally correlated with lower SG channel head dose rates. However, the decrease in dose rates is not significant relative to the scatter in the data, suggesting that this is a minor effect. This is an expected effect, confirming that the main consideration with respect to RCP run time is the potential for particulate settling and associated consequences. No effects on the RCS loop piping or SG exterior dose rates were observed.

- There was no definitive correlation observed between RCP run time and the occurrence of extended release. Data include run times as short as 1 hour and as long as 57 hours. As noted above, Strategies 2 and 3 with RCPs secured at forced oxidation do lead to a higher probability of an extended release. However, the probability of an extended release may be greater if the run time is less than about 6 hours. That is, while shorter run times (< 6 hours) do not always lead to extended release, they lead to an increase in the probability of extended release.

It should be noted that in the main data set evaluated, Strategy 2 and Strategy 3 together constituted only 14% of the shutdowns evaluated. This limits the conclusions of this assessment to first order effects, i.e., effects large enough to be observed in a limited data set in which other factors may create uncharacterized variability.

7.2 Plant commissioning – Hot Functional Testing

A. Tigeras from EDF, presented information on the study of various hot functional testing options [Tigeras, et.al, 2016 c] to be used for Flamanville 3, an EPR PWR.

The main purpose of commissioning tests is to demonstrate, that the plant structures, systems and components are capable of safe and reliable operation in accordance with their design specification, their performance objectives and their safety requirements. A phased approach is applied for plant commissioning. It is carried out in three main phases:

- Individual System Tests including initial construction and individual system tests.

- Pre-Core Loading Tests including Cold Functional, Hydrostatic and Hot Functional Tests of the Reactor coolant system, Secondary systems and Fuel loading Preparation.

- Power Escalation Tests including fuel loading, cold and hot pre-critical tests, initial criticality, and power ascension up to commercial operation.

The chemistry and radiochemistry follow up deals with several roles and objectives depending on the plant commissioning phases [Tigeras, et.al, 2016 c]:

- To ensure the cleanness of the circuits.

- To verify the suitable operation of equipment related to chemical or radiochemical actions such as additives injection, filtration, purification, degassing, sampling, on-line measurements.

- To apply the appropriate chemical conditioning of systems in order to limit the material generalized corrosion and the associated consequences: source term, personal dose, effluents, waste.

Commissioning tests are currently in progress.

7.3 Plant start-up after long shut-down

As explained in section 6.1, safety aspects are of very high importance to allow restarting NPP in Japan after Fukushima accident of 2011. It took a long time to get permission for restart due to review for checking the conformity to New Nuclear Regulation Authority Requirement and newly required pre-service inspections. Through two years without any operating plant, now two PWRs (Sendai) are on operation and few more plants are waiting for early permission for start-up, Figure 7-1. The latest activities of the water chemistry group in Japan, including four topics, are as follows [Katsumura et al., 2016].

1. Latest situation of NPP operation in Japan and future prospects;

2. Water chemistry control for long-term plant lay-up and for safety plant restart;

3. Contribution of water chemistry group to minimizing the contaminated water in Fukushima;

4. Daiichi NPP as well as cleaning it up;

5. Long-term strategies for technical transfer in the water chemistry group until the termination of decommissioning of Fukushima Daiichi NPP.
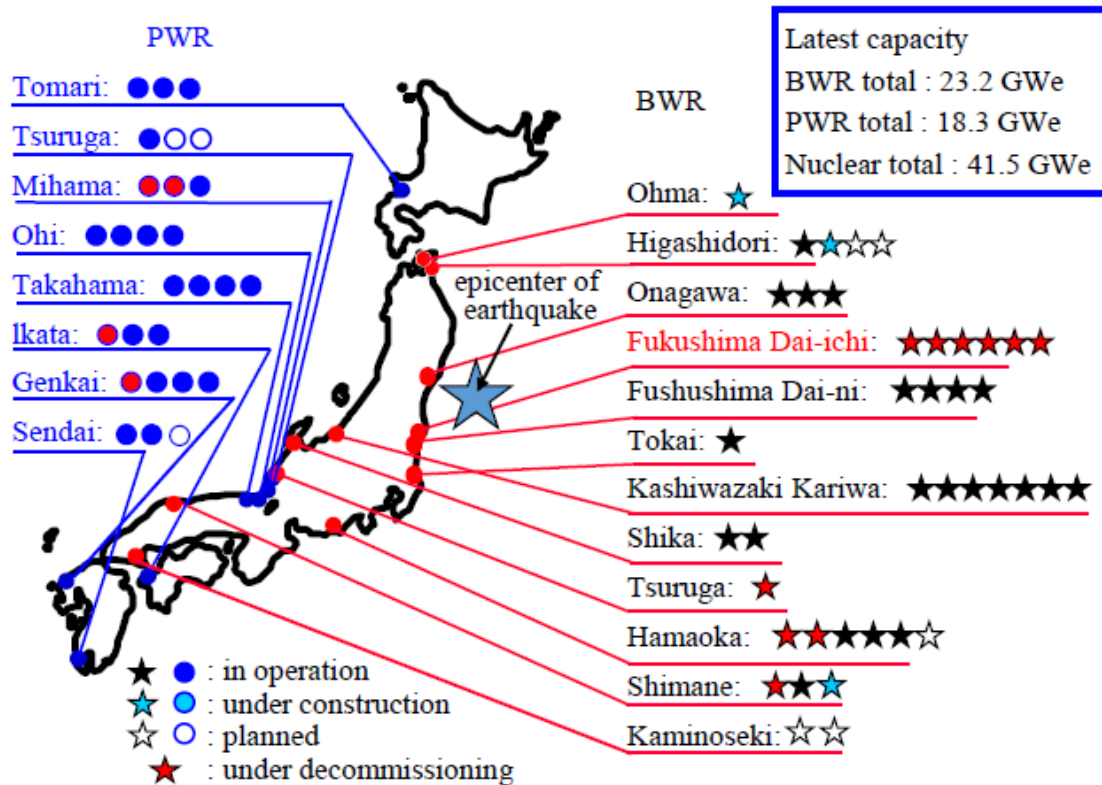
Figure 7-1   Map showing location of Japanese light water reactors [Katsumura et al., 2016]

Many PWRs in Japan are under the process of restarting operation after the Fukushima accident, and a careful water chemistry management on the primary side and the secondary side is required for all the plants to restart successfully Figure 7-2.
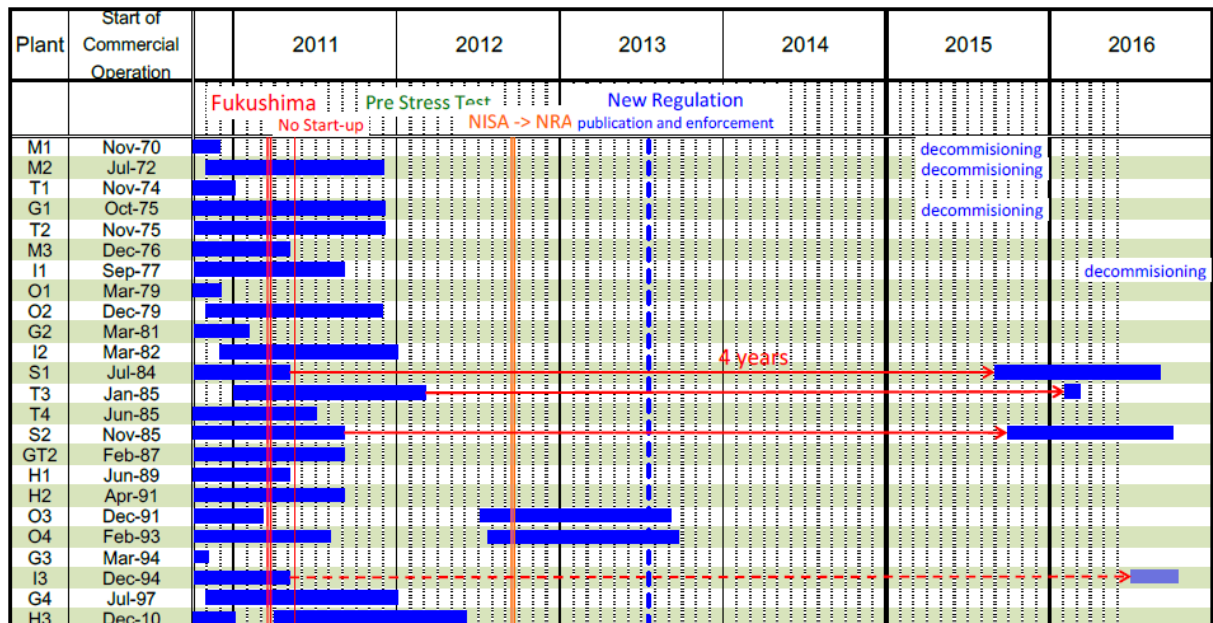

Figure 7-2   Recent working schedule of Japanese PWR plants where M = Mihama ; T = Takahama ; G = Genkai ; O = Oho; I= Ikata; S= Sendai; H= Tomari; GT = Tsuruga [Ishihara et al., 2016]

8   High Temperature and Advanced Reactors

An interesting paper from India is evaluating the design of an Advanced Heavy Water Reactor (AHWR) with the objective of utilizing the abundant thorium, a fertile material, in the fuel. It is one of the next generation reactor types. It is proposed to use $PuO_2 - ThO_2$ and $^{233}UO_2 \cdot ThO_2$ as fuel in an open cycle. It is a tube type boiling water reactor with a vertical core and uses the concept of natural circulation for core cooling. Also, it uses heavy water (D_2O) as moderator and light water as main coolant. The structural material of the main heat transport system is stainless steel AISI-304. In the core, Zr-2.5 Nb and Zircaloy-2 are proposed to be used. The boiling light water coolant exits the core with 18% steam quality. Hence, a two phase mixture travels through the stainless steel tail pipes and reaches the steam separator which is clad with stainless steel. The large stainless steel surface (area of 11540 m2) requires protection from Intergranular Stress Corrosion Cracking (IGSCC) and the reducing condition to the Main Heat Transport system would be obtained either by Hydrogen with Noble Metal Chemical Addition (NMCA) or by hydrazine addition [Velmurigan, et al., 2016].

The radiolysis of water increases with gamma radiation dose for a given concentration of gadolinium with a linear increase in hydrogen volume. This increase can be fitted into linear curve and from the slopes of the lines G values for hydrogen generation can be calculated. The change in GH_2 with gadolinium concentration is plotted in Figure 8-1.
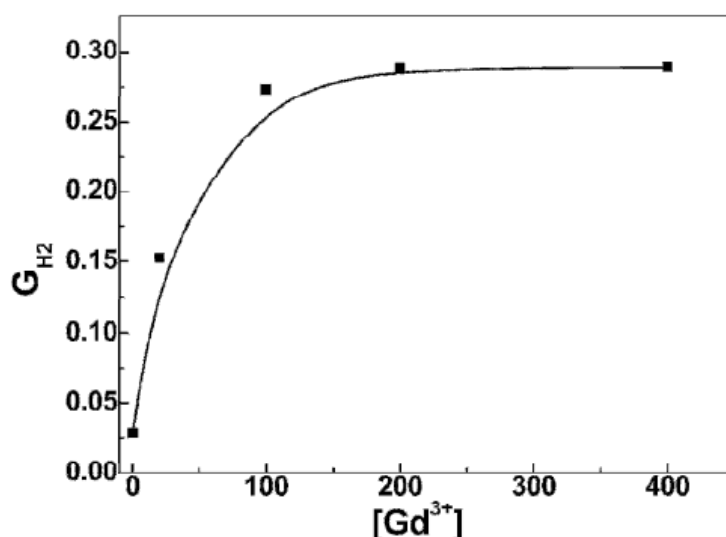

Figure 8-1   Variation in the hydrogen yield as a function of gadolinium concentration Velmurigan et al., 2016].

For the MYRRHA Accelerator Driven System currently under development at the Belgian Nuclear Research Centre SCK CEN, liquid lead bismuth eutectic (LBE) is foreseen as a coolant. For long-term operations of such a non-isothermal nuclear system, chemical effects, such as formation and deposition of oxides, formation of (volatile) radionuclides, corrosion of structural steels, etc. need to be mastered and controlled. The main mitigation mechanism considered is the control of dissolved oxygen in LBE. This needs to be controlled in a narrow window to prevent coolant oxidation or dissolution of steel alloying elements and subsequent formation of solids in LBE. Under accident conditions, steam can be released in the LBE or in the cover gas, due to e.g. the failure of a heat- exchanger or due to water sprinkling on the LBE in the reactor pool in case of fuel release.

Although the LBE-water reaction is often seen as benign, chemical equilibrium calculations show that the release of water can lead to hydrogen generation, as shown on Figure 8-2, a significant increase in the dissolved oxygen concentration or to enhanced formation of oxides. [Rosseel, et al., 2016].
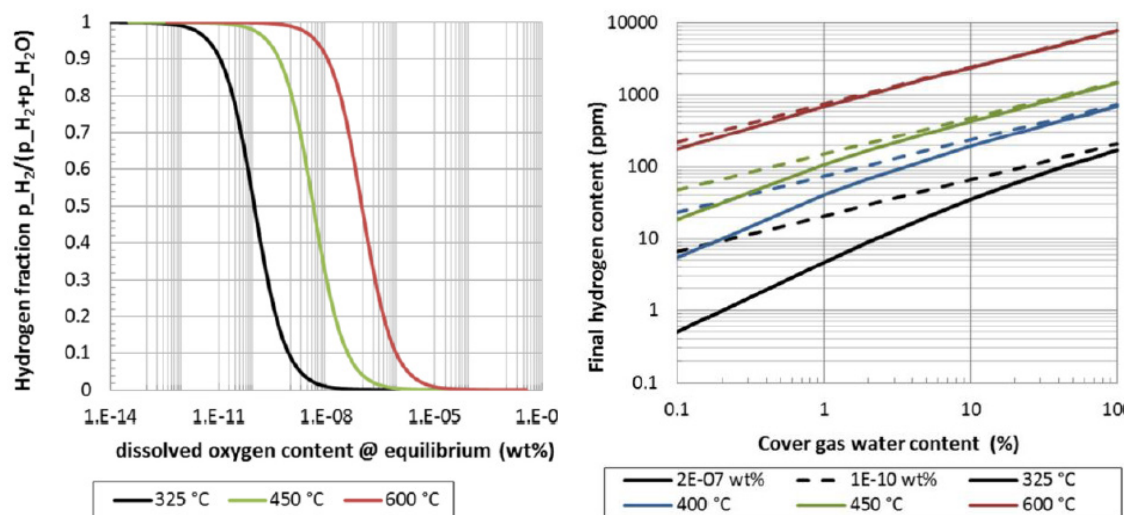
Figure 8-2   Left: Hydrogen content in the cover gas due to water-LBE interaction as a function of the oxygen content. Right: amount of hydrogen in the cover gas for LBE water-interaction in MYRRHA, as a function of the water content in the cover gas. [Rosseel et al., 2016].

At high initial dissolved oxygen concentrations, water-LBE interaction can be considered benign. In this case, water has little influence, neither on the dissolved oxygen content nor on the amount of hydrogen produced. The presence of large quantities of impurities such as iron may change this picture significantly. If impurities are released in LBE, this can lower the local oxygen content significantly due to the formation of oxides. Adding water to LBE with a high impurity content and at low dissolved oxygen concentrations will not lead to large changes in the dissolved oxygen content, as most of the oxygen added by water dissociation binds with impurities present to form oxides. Impurities, however, can stimulate dissociation of water and consequently lead to an increase in the amount of hydrogen produced. Over 20% of the water initially present can be converted to hydrogen gas [Rosseel, et al., 2016].

The design of single phase water cooling circuits is being developed as an option for the tritium breeder blankets of the European demonstration fusion power plant (DEMO). This has been based on generic PWR primary circuit thermal hydraulics modified to suit the heat transfer requirements of the plant, including the chemistry regime. Adaptation of the chemistry is required, at least due to the nominal material selection of Eurofer, a reduced activation ferritic-martensitic steel with limited industrial application [Burrows et al., 2016].

To access the extensive operating experience and supporting fundamental science from worldwide LWR fleets, a framework has been proposed by British researchers to allow development of a technically underpinned water chemistry. The relevance of existing international guidelines is considered in view of the DEMO breeder blanket cooling conditions and the need is outlined for a corresponding set of conceptual water chemistry guidelines containing control parameters, target values and action ranges. These would facilitate development of the cooling circuit by consolidating the chemistry drivers arising from functional requirements, materials behaviour and service conditions. In some cases, these are synergistic while in other cases, the need to reconcile competing requirements is identified, as well as knowledge gaps which require technical development.

Importantly, (i) the corrosion behaviour of one of the main pressure boundary materials, Eurofer-97 is not well known and (ii) the concentrations of oxidising species expected to be produced by radiolysis of the coolant have not been assessed in detail. Close control of feedwater impurities and hydrogen dosing are likely to be central and the value of a non-volatile alkalising agent should be investigated. Mitigating options currently employed in LWR fleets such as Zn addition and NMCA/OLNC should be considered once a more mechanistic understanding of the materials

References

Alekseev P. and Shimkevich A. "*A Concept for Inhibiting Corrosion Rate of the PWR Fuel Cladding by the Electro–Reduced Aqueous Coolant*". NPC 2016. 20th International Nuclear Plant Chemistry Conference. Nuclear Institute. Brighton UK; 2-7th October 2016.

Alos-Ramos O., Lucas E., Bachet M., Moll R., Habert M., H. Schneider H., Ortega-Rodriguez U. and Pierre M. "Enhance of Silica Management in French PWR Fleet". NPC 2016. 20th International Nuclear Plant Chemistry Conference. Nuclear Institute. Brighton UK; 2-7th October 2016.

Aoki M., Tanabe T., Maeda A., Ishihara N. and Shoda Y. "*Experiences of Takahama Unit 3 and 4 Plant Start-up Water Chemistry Control After Long Term Suspended Operation*". NPC 2016. 20th International Nuclear Plant Chemistry Conference. Nuclear Institute. Brighton UK; 2-7th October 2016.

Arcis H., Ferguson J., Applegarth L., Zimmerman G., Cox J., Pye C., Sasidharanpillai S., Hussey D., Wells D., and Tremaine P., "*Speciation and Thermodynamic Stability of Boric Acid, Borate and Polyborates under PWR Primary Coolant Conditions by AC Conductivity and Raman Spectroscopy*", NPC 2016. 20th International Nuclear Plant Chemistry Conference. Nuclear Institute. Brighton UK; 2-7th October 2016.

Atkinson C. and Morris R. "*Determination of the Effects of Hydrazine on Ion Exchange Resins*". NPC 2016. 20th International Nuclear Plant Chemistry Conference. Nuclear Institute. Brighton UK; 2-7th October 2016.

Atkinson C., Morris R. and Chloe Watson and Watson C., "*Operational Experience of Palladium Doped Resin in Stator Cooling Water Circuits*", NPC 2016. 20th International Nuclear Plant Chemistry Conference. Nuclear Institute. Brighton UK; 2-7th October 2016.

Bachet M., Monchy-Leroy C. and Bretelle J-L., "*Main Conclusions from the MAI Workshop on Silver 110m Contamination in Pressurized Water Reactors*", NPC 2016. 20th International Nuclear Plant Chemistry Conference. Nuclear Institute. Brighton UK; 2-7th October 2016.

Balaji V., Chandramohan P., Srinivasan M.P. Rangarajan S. and Velmurugan S. "*Dissolution behavior of mixed ferrites containing zinc in oxidizing formulation*" NPC 2016. 20th International Nuclear Plant Chemistry Conference. Nuclear Institute. Brighton UK; 2-7th October 2016.

Banks A., Scenini F., Connolly B., McGurk J. and Henshaw J., "*Modelling and Experiments on Localised CRUD Deposition*", NPC 2016. 20th International Nuclear Plant Chemistry Conference. Nuclear Institute. Brighton UK; 2-7th October 2016.

Bao Yi-Chen, Shi Xiu-qiang, Zhang Le-fu and, Yang Chen. "*Corrosion Inhibition Properties of NaNO2, Na2MoO4 and TTA-Na Compounds on Materials of Cooling Water System*", NPC 2016. 20th International Nuclear Plant Chemistry Conference. Nuclear Institute. Brighton UK; 2-7th October 2016.

Barreda F-A., Guérin L. and Huerta Ortega G, "*Physical Speciation and Characterization of Corrosion Products in Nuclear Environments by On Line Sampling Device*", NPC 2016. 20th International Nuclear Plant Chemistry Conference. Nuclear Institute. Brighton UK; 2-7th October 2016.

Beal K., Million-Picallion L., Lefèvre G., Berger G., Delaunay S., Goujon C. and Bretelle J-L., "*Formation and Consolidation of Hard Sludge under Secondary Circuit Conditions*", NPC 2016. 20th International Nuclear Plant Chemistry Conference. Nuclear Institute. Brighton UK; 2-7th October 2016.

Benfarah1 M., You D., Jobert T., and Debier1 D., "*Study of PWR Contamination by [110m]Ag Using Thermochemical Simulation of Silver, Iodine and Silver Iodide Under PWR Coolant Conditions*", NPC 2016. 20th International Nuclear Plant Chemistry Conference. Nuclear Institute. Brighton UK; 2-7th October 2016.

Bengtsson B. Svanberg P., Arguelles D., Eek W., "*Safety & Radiation Benefits Using Frequent and Optimised Fuel Cleaning*", NPC 2016. 20th International Nuclear Plant Chemistry Conference. Nuclear Institute. Brighton UK; 2-7th October 2016.

Bowskill S., Dickinson S., Garbett K., Hinds K., Scrancher M. and Welsh B., "*Modelling of Fission Product Behaviour in Sizewell B Coolant*", NPC 2016. 20th International Nuclear Plant Chemistry Conference. Nuclear Institute. Brighton UK; 2-7th October 2016.

Brussieux C., Pages H., Guillodo M., Fourchotte J.P., Mourges A., Clinard M.H. and Engler N., "*BEATRICE: a unique test facility simulating the EPR primary circuit for corrosion studies*", NPC 2016. 20th International Nuclear Plant Chemistry Conference. Nuclear Institute. Brighton UK; 2-7th October 2016.

Buddas S. and Mäkinen M., "*Abnormal Solid Matter Observations at Loviisa NPP Unit 2*", NPC 2016. 20th International Nuclear Plant Chemistry Conference. Nuclear Institute. Brighton UK; 2-7th October 2016.

Bultot M., Dacquait F., Tevissen E., Schildermans K., and Lecocq R., "*Zinc effect on the primary circuit contamination of a Belgian PWR using the OSCAR V1.3 code*", NPC 2016. 20th International Nuclear Plant Chemistry Conference. Nuclear Institute. Brighton UK; 2-7th October 2016.

Burrows R., Harrington C., Baron-Wiechec A. and Warren A. "*Development of Conceptual Water Chemistry Guidelines for Water Coolant Circuits of a Demonstration Fusion Power Reactor*", NPC 2016. 20th International Nuclear Plant Chemistry Conference. Nuclear Institute. Brighton UK; 2-7th October 2016.

Carlin B., Camarda L. and Roth M. "*Mitigation of ETA Related Anion Resin Kinetic Impairment in PWR Condensate Polishers*", NPC 2016. 20th International Nuclear Plant Chemistry Conference. Nuclear Institute. Brighton UK; 2-7th October 2016.

Chi Bum Bahn, Hoyeon Bae, Taeho Kim and Ji Hyun Kim, "*Effects of Zinc Injection and Dissolved Hydrogen Concentration on ZIRLO™ Oxidation*", NPC 2016. 20th International Nuclear Plant Chemistry Conference. Nuclear Institute. Brighton UK; 2-7th October 2016.

Choi S., Fruzzetti K., Caravaggio M., Shulder S., Marks C., Reinders J., Anisa Mechler A. and Marc Kreider M. "*Filming Amines: A Pathway to Wider Use in PWRs*", NPC 2016. 20th International Nuclear Plant Chemistry Conference. Nuclear Institute. Brighton UK; 2-7th October 2016.

Cook W., Brown G., Smith B., Gardner E., and Stuart C., "*Evolution of Primary Heat Transport System Radiation Fields at the Point Lepreau Nuclear Generating Station following Mid-Life Refurbishment*", NPC 2016. 20th International Nuclear Plant Chemistry Conference. Nuclear Institute. Brighton UK; 2-7th October 2016.

Coriou, H., Grall, L., Neunier, J., Pelras, M., and Willermoz, H. "*The Corrosion of Zircaloy inVarious Alkaline Media at High Temperature*", Corrosion of Reactor Materials, Vol. II, 193,IAEA, Vienna. 1962.

Dacquait F., Bultot M., Pipet G., Francescatto J., Broutin F., Benfarah M. and Mondit P., "*110mAg behaviour in PWRs: Lessons learnt from the EMECC campaigns*", NPC 2016. 20th International Nuclear Plant Chemistry Conference. Nuclear Institute. Brighton UK; 2-7th October 2016.

Davis A., Welsh B. and Scrancher M., "*The Use of Gas Sampling Equipment to Detect Failed Fuel Prior to Long Term Storage at Sizewell B Power Station*", NPC 2016. 20th International Nuclear Plant Chemistry Conference. Nuclear Institute. Brighton UK; 2-7th October 2016.

Degand F., Normand-Guémas C., Becker G., Clinard M-H. and Fournier L., "*Development of a Dynamic Model (Opera) in order to Optimize Fluids Management and Limit Tritium Release in EPRTM Systems*", NPC 2016. 20th International Nuclear Plant Chemistry Conference. Nuclear Institute. Brighton UK; 2-7th October 2016.

Delaunay S., Goujon C., Bescond A., Flaus M., Tireau J., Burger E., Gabriel D. and Bretelle J-L. "*Study of film-forming amine application in PWR secondary circuit layup protection*", NPC 2016. 20th International Nuclear Plant Chemistry Conference. Nuclear Institute. Brighton UK; 2-7th October 2016.

Devlin M., Rosell A., Lillfors-Pintér C., and Bengtsson B., "*Membrane Filtration and Investigation of Filter Fouling Mitigation Strategies*", NPC 2016. 20th International Nuclear Plant Chemistry Conference. Nuclear Institute. Brighton UK; 2-7th October 2016.

Dickinson S., Wells D., Bachet M., Banks A., Eaker R., Marks C. and Tremaine P., "*Solubility of Cobalt Oxide and other Cobalt Compounds: Development of MULTEQ models*", NPC 2016. 20th International Nuclear Plant Chemistry Conference. Nuclear Institute. Brighton UK; 2-7th October 2016.

Diego G. and Merino S. "*Microstructural characterization of sludge steam generator from Spanish NPP´s*", NPC 2016. 20th International Nuclear Plant Chemistry Conference. Nuclear Institute. Brighton UK; 2-7th October 2016.

Drexler A., Schütz S., Duca J., Manzi R., Galarza G., 3, Grasso G., Bejarano R., Carvalho A., Francisco A., Portugal F., Oliveira M., Menezes M., Rubenich M., and Ferreira W., "Chemistry Concept for Dose Rate Minimization Treatment of New and Decontaminated PWRs and PHWRs", NPC 2016. 20th International Nuclear Plant Chemistry Conference. Nuclear Institute. Brighton UK; 2-7th October 2016.

Engler N., Marion A., Fournier L., Rahmouni K., El Euch C. and Bojinov M. "*Steam Generator Tube Release: Assessment by the Use of Electrochemical Impedance Spectroscopy* ", NPC 2016. 20th International Nuclear Plant Chemistry Conference. Nuclear Institute. Brighton UK; 2-7th October 2016.

EPRI 2001. "*Effect of Boron Concentration on Alloy-690 Corrosion Product Release Rates - Results at 325°C and 285°C*". EPRI, Palo Alto, CA: 2001. 1011744.

Fruzzetti K. Marks C., Jeff Reinders J., McElrath J. and Wells D. "*Evaluation of Potassium Hydroxide for Reactor Coolant pHT Control in Western PWRs*", NPC 2016. 20th International Nuclear Plant Chemistry Conference. Nuclear Institute. Brighton UK; 2-7th October 2016, a.

Fruzzetti K. Kreider M. MoroneyV., Schmitt K, McCree Mechler A., and Marks C. "*PWR Secondary Dispersant Operating Experience Update*", NPC 2016. 20th International Nuclear Plant Chemistry Conference. Nuclear Institute. Brighton UK; 2-7th October 2016, b.

Fruzzetti K., Sawochka S. and Duncanson I., "*Assessment of Possible Dispersant Effects on South Texas Project Unit 1Condensate Demineralizer Resin Performance*", NPC 2016. 20th International Nuclear Plant Chemistry Conference. Nuclear Institute. Brighton UK; 2-7th October 2016, c.

Gath J., Maurer H. and Wagner H., "*Conventional Resin Cation Exchangers Versus EDI for CACE Measurements – An Ion Chromatography Study*", NPC 2016. 20th International Nuclear Plant Chemistry Conference. Nuclear Institute. Brighton UK; 2-7th October 2016.

Nomenclature

AISI	American Iron and Steel Institute
ALARA	As Low As Reasonably Achievable
ALARP	As Low As Reasonable Practicable
ANTI	ANT International
AOA	Axial Offset Anomaly
cc/kg	cubic centimetre (per kg): used for H_2 concentration in RCS = ml/kg (under normal pressure and temperature)
CCW	Closed Cooling Water
CGR	Crack Growth Rate
CIPS	CRUD Induced Power Shift
CNSC	Canadian Nuclear Safety Commission
CP	Corrosion Product
CS	Carbon Steel
CPP	Condensate Polishing Plant
CRUD	Acronym for "Chalk River Undefined Deposits"
CS	Carbon Steel
CVCS	Chemical and Volume Control System
DEHA	Diethylhydroxylamine
DF	Decontamination Factor
DH	Dissolved Hydrogen
DO	Dissolved Oxygen
DR	Dose Rate
EBA	Enriched Boric Acid
ECP	Electro Chemical Potential
EdF	Electricité de France
EIS	Electrochemical Impedance Spectroscopy
EPR	European Pressurized Water Reactor
EPRI	Electric Power Research Institute, USA
FFA	Film Forming Amines
FHD	Forced Helium Dehydrator
FW	Feed Water
HPUF	Hydrogen Pickup Fraction
ICP	Inductively Coupled Plasma optical emission spectrometry
IER	Ion Exchange Resin
IGSCC	Intergranular Stress Corrosion Cracking
LBE	Liquid Lead Bismuth Eutectic
LPR	Long-path Recirculation
LTU	Long-term use
MA	Mill Annealed
NMCA	Noble Metal Chemical Addition
NPP	Nuclear Power Plant
ODA	Octadecylamine
ORE	Occupational Radiation Exposure
ORP	Oxidation–reduction Potential
PAA	PolyAcrylic Acid (dispersant)
PAMA	Poly (acrylic acid-co-maleic acid)
PHWR	Pressurized Heavy Water Reactors
ppb	part per billion = µg/kg
ppm	part per million = mg/kg
PWR	Pressurized Water Reactor
PWSCC	Primary Water Stress Corrosion Cracking
REA	Boron and Water Make-up System to the reactor Coolant of French PWR
RCP	Reactor Coolant system of French PWR or Reactor Coolant Pump
RCS	Reactor Coolant System
RHRS	Residual Heat Removal System

Unit conversion

TEMPERATURE		
°C + 273.15 = K	°C × 1.8 + 32 = °F	
T(K)	T(°C)	T(°F)
273	**0**	32
289	16	61
298	25	77
373	**100**	212
473	**200**	392
573	**300**	572
633	360	680
673	**400**	752
773	**500**	932
783	510	950
793	520	968
823	550	1022
833	560	1040
873	**600**	1112
878	605	1121
893	620	1148
923	650	1202
973	**700**	1292
1023	750	1382
1053	780	1436
1073	**800**	1472
1136	863	1585
1143	870	1598
1173	**900**	1652
1273	**1000**	1832
1343	1070	1958
1478	1204	**2200**

MASS	
kg	lbs
0.454	**1**
1	2.20

DISTANCE	
x (µm)	x (mils)
0.6	0.02
1	0.04
5	0.20
10	0.39
20	0.79
25	0.98
25.4	**1.00**
100	3.94

PRESSURE		
bar	MPa	psi
1	0.1	14
10	**1**	142
70	7	995
70.4	7.04	**1000**
100	10	1421
130	13	1847
155	15.5	2203
704	70.4	**10000**
1000	100	14211

STRESS INTENSITY FACTOR	
MPa√m	ksi√inch
0.91	**1**
1	1.10

Radioactivity
1 Sv = 100 Rem
1 Ci = 3.7×10^{10} Bq = 37 GBq
1 Bq = 1 s^{-1}