

Water Chemistry Management for the Primary Circuit of the First EPR Unit during Hot Functional Testing

Zhu Wang, Zhi-Wei Ge, and Zi-Tao Liu

ABSTRACT

The paper describes in detail the water chemistry control during the hot functional testing (HFT) of the first European pressurized reactor (EPR) unit worldwide, and focuses on the water chemistry control during passivation treatment of the component surfaces in the primary circuit with hydrogen injection, higher $\text{pH}_{300^\circ\text{C}}$ and impurity control. Two identical surveillance coupons made of Inconel 690 TT steam generator (SG) tube samples were placed in the reactor pressure vessel (RPV) to evaluate the final passivation results. Water chemistry data and metallographic analysis results show that an excellent protective film was formed on the surface of the tubes, which reduces the corrosion rate of materials and the release of corrosion products, thereby also reducing radiation source terms during commercial operation of the unit. In addition, a brief comparison of the passivation film and passivation process between two types of the 3rd generation pressurized water reactors (PWRs), especially the hydrogen injection and zinc injection technologies, was made. The benefit of the passivation process during HFT for the dose rate is preliminary, and the dose rate reduction effectiveness also depends on the applied water chemistry control methods during future power operation of the unit.

NOMENCLATURE AND ABBREVIATIONS

HFT	hot functional testing
EPR	European pressurized reactor
SG	steam generator
RPV	reactor pressure vessel
RCS	reactor coolant system
PZR	pressurizer
CDS	coolant degasification system
SHE	standard hydrogen electrode
DH	dissolved hydrogen
CVCS	chemical and volume control system
RIS/RHR	residual heat removal system
CSS	coolant storage system
SEM	scanning electron microscope
TEM	transmission electron microscope
AP 1000	a 3rd generation PWR designed in America

INTRODUCTION

Hot functional testing (HFT) is an important task during pressurized water reactor (PWR) commissioning. It begins with the closure of the reactor pressure vessel (RPV) head and water injection into the primary circuit. The mechanical energy produced by the main cooling pumps is the heat source to heat up the reactor coolant system (RCS) to nominal operating temperature, and a series of tests is conducted during all the stages of HFT to confirm the availability and operability of all systems relevant for safety functions and operation of the unit.

During HFT, the formation of an excellent passivation film on the component surfaces in the primary circuit is one of the important tasks, especially for the very large surface area of the steam generator (SG) tube bundles. The quality of the passivation film will affect the corrosion rate of the component surfaces, and thus the nuclear safety and the radiation source term.

The EPR (European pressurized reactor) is a 3rd generation pressurized water reactor (PWR). The main materials used in the primary circuit are as follows: Inconel 690 TT for SG tubes, the alloy M5™ from Framatome for the fuel assemblies, and stainless steel for the pipes and other

components. Passivation of the primary circuit is guaranteed by performing adequate water chemistry control and conditioning.

FORMATION MECHANISM OF THE PASSIVATION FILM

A passivation film will form on the surfaces in the primary circuit at nominal temperature. The passivation process can be divided into four steps.

- Step 1: Selective dissolution of nickel (Ni) (nickel is released into the fluid) and nucleation of chromium (Cr) compounds (oxides and hydroxides) take place. At this stage, the oxides predominantly consist of Cr-rich oxide and minor spinel (Ni, Fe) $(\text{Fe, Cr})_2\text{O}_4$ and $\text{Ni}(\text{OH})_2$ oxide phases.
- Step 2: Coalescence of Cr_2O_3 nuclei creates a continuous layer of Cr_2O_3 with an outer layer of $\text{Cr}(\text{OH})_3$; while $\text{Cr}(\text{OH})_3$ dehydrates and converts by the transfer of Cr to Cr_2O_3 , the thickness of the Cr_2O_3 starts to increase.
- Step 3: $\text{Cr}(\text{OH})_3$ conversion continues and leads to a thickening of the Cr_2O_3 layer.
- Step 4: Ni is transferred through this oxide layer to form $\text{Ni}(\text{OH})_2$ on top of it and/or is released in the form of Ni^{2+} ions into the coolant.

Therefore, the final oxide film can be simply divided into two layers. The outer layer is spinel, loose and unstable, and is not protective because of its deficiency in chromium. The inner layer is rich in chromium, nickel oxide free, amorphous and dense, with a thickness ranging from several nanometers to several tens of nanometers. This layer has the protective function of preventing or restricting fluid exchange with the base metals to inhibit metal corrosion, which is beneficial to source term control.

Since the water chemistry during HFT plays a key role in the formation of the passivation film, it is necessary to condition and control the water chemistry in the primary circuit. The process includes pH, elec-

trochemical potential conditioning and impurity control. Of course, the thermal parameters of the reactor coolant system (RCS), especially the temperature of the coolant, can affect the corrosion of the materials, the passivation process and the transport of corrosion products.

WATER CHEMISTRY CONTROL DURING HFT OF THE EPR UNIT

The planned schedule of HFT of the 1st EPR unit is divided into three consecutive parts: start-up and heat-up of the coolant for the first time to nominal operating conditions, a temporary shutdown and a second heat-up of the primary circuit for further functional testing at nominal

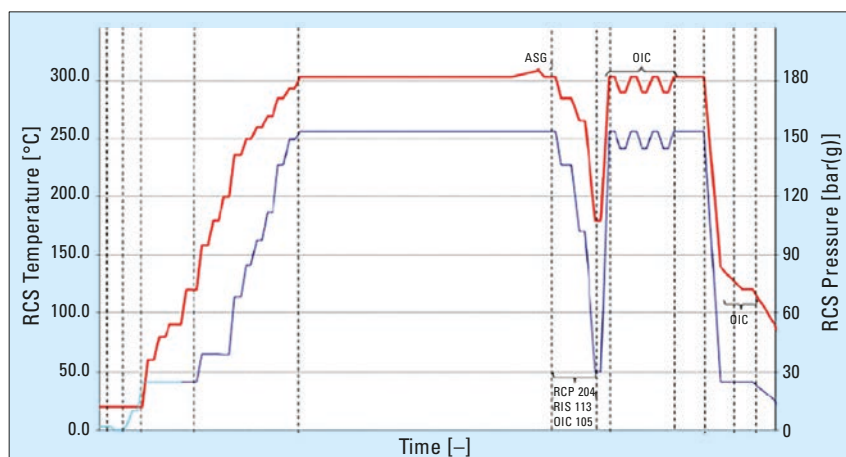


Figure 1:
Schedule planned for HFT of the EPR unit.

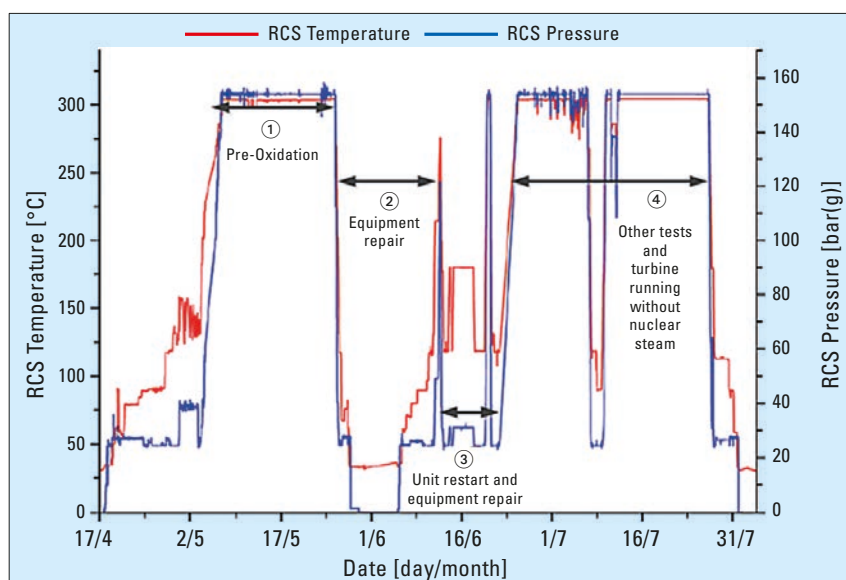


Figure 2:
Actual process of HFT of the EPR unit. The passivation treatment was performed in Phase 1 and finished by a thorough purification of the primary circuit for the removal of the non-protective outer oxide layer and impurities during shutdown.

operating conditions, and shutdown operations (see Figure 1).

However, due to equipment failure and other reasons, the actual process of HFT was split into two main stages, as shown in Figure 2. The passivation treatment was performed during the first main stage of HFT and finished by a shutdown.

Process performance involved several new chemistry technology improvements such as hydrogen injection and boric acid injection, forced oxygenation during cold shutdown and so on. This is described and discussed in the following.

Oxygen Control during Startup

To prevent stress corrosion cracking of the electrical heater rods in the pressurizer (PZR) at high levels of oxygen and high temperatures, oxygen in the primary circuit should be removed to less than $100\mu\text{g}\cdot\text{kg}^{-1}$ before it is heated up to 90°C . At this temperature, the steam bubble in the PZR head space is established.

First, physical methods are used to remove residual gas in the primary circuit, including static degassing and dynamic degassing of the RCS by step by step operation (inching) of the main cooling pumps; then, dissolved gas is removed by the degasser of the coolant degasification system (CDS). Finally, chemical methods are used to reduce the oxygen concentration to meet the requirement of the specification.

1) Physical degassing

Part of the gas in the reactor coolant system will be removed by gravity or pressure during HFT, that is, by opening the degassing valve at the top of the RPV, in the PZR and at the shaft seal of the main coolant pumps during filling of the RCS and during pressure increase. If the residual gas volume after system static degassing does not meet the requirement, dynamic degassing is performed by inching one after the other of the four main coolant pumps so the residual gas pockets in the SG tube bundles will be removed by the forced water flow.

The residual gas volumes of the 1st and 2nd static degassing were 24.8Nm^3 and 28.2Nm^3 , respectively, meeting the requirement; therefore dynamic degassing was not necessary. Then the degasser of the CDS was put into service to reduce the gas volume in the main circuit to 10Nm^3 and the oxygen concentration of the coolant decreased to $5.25\text{mg}\cdot\text{kg}^{-1}$. For further reduction of the oxygen content of the coolant, chemical degassing was performed.

2) Chemical degassing

Chemical degassing is done by injecting hydrazine into the RCS. Because there is no fuel loading and no radiation field, the reaction between oxygen and hydrazine would be very slow. To facilitate the reaction, lithium (Li) injection should be done prior to hydrazine injection at 60°C , with a lithium target value of approximately $2.0\text{mg}\cdot\text{kg}^{-1}$ for adjustment of the $\text{pH}_{25^\circ\text{C}}$ to about 10.5.

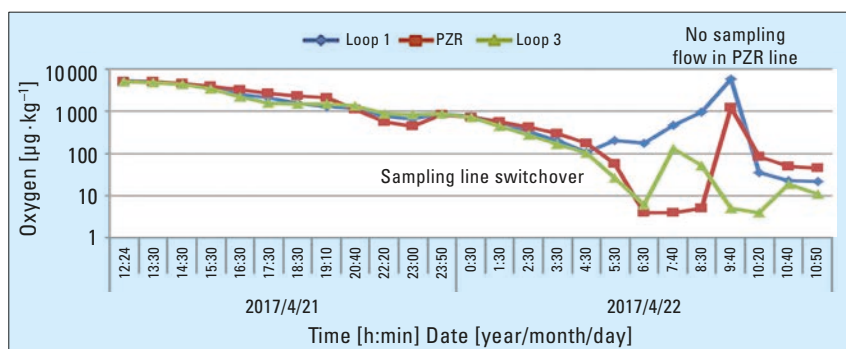


Figure 3: Dissolved oxygen concentration in the RCS during the chemical degassing with hydrazine. Further heat-up of the primary circuit was started at around 10:00 a.m. when the oxygen content of the coolant in the PZR sampling line fell to $100\mu\text{g}\cdot\text{kg}^{-1}$.

During the HFT startup, the final lithium concentration was $2.36\text{mg}\cdot\text{kg}^{-1}$, and within 21 hours after hydrazine injection, the oxygen concentration of the coolant decreased from $5\text{mg}\cdot\text{kg}^{-1}$ to $21.6\mu\text{g}\cdot\text{kg}^{-1}$, which met the requirement. Figure 3 shows the trend of the dissolved oxygen concentration during chemical degassing with hydrazine.

When the oxygen content of the coolant from the PZR sampling line fell below $100\mu\text{g}\cdot\text{kg}^{-1}$, further heat-up of the primary circuit was started at around 10:00 a.m. In order to avoid or mitigate a lithium concentration effect on the material of the PZR, about $35\text{mg}\cdot\text{kg}^{-1}$ of boron was injected before formation of the steam bubble in the PZR. The boron concentration of the coolant remained at about $20\text{mg}\cdot\text{kg}^{-1}$ during subsequent passivation treatment of the primary circuit.

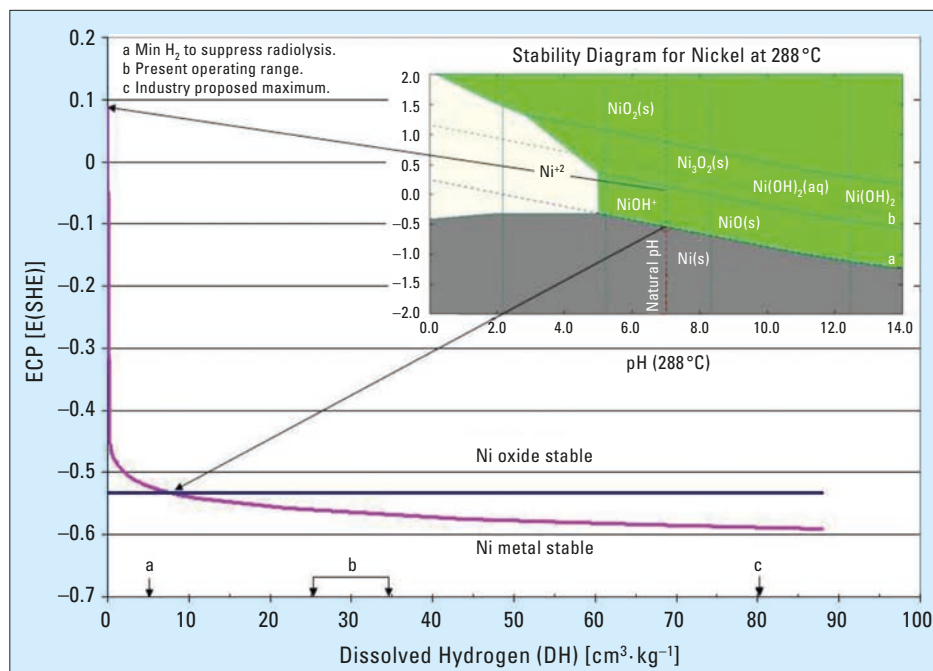


Figure 4:
Regions of stability of Ni and NiO as
a function of the potential E(SHE) and
the dissolved hydrogen concentra-
tion.

Water Chemistry Control during Passivation Treatment and Subsequent Shutdown

About $2\text{mg}\cdot\text{kg}^{-1}$ lithium and $20\text{mg}\cdot\text{kg}^{-1}$ boric acid were maintained in the RCS during passivation treatment of the primary circuit. In addition, hydrogen was injected into the RCS to establish a reducing environment in the coolant, which is beneficial for the formation of a more stable oxide layer on the surface of Inconel alloys. Figure 4 shows the influence of the potential E(SHE) and the dissolved hydrogen (DH) on the stability of Ni and NiO. Hydrogen partial pressures at which only metallic Ni is stable will lead to a NiO free surface layer and minimize Ni release to the coolant. The higher the hydrogen concentration, the more compact and stable the oxide film.

For passivation treatment of the component surface in the primary circuit, the target value of the hydrogen concentration was about $35\text{mL}\cdot\text{kg}^{-1}$. The temperature of the coolant was stable and was maintained above 283°C . The duration of the passivation treatment was more than 300 hours. The mixed-bed filter of the chemical and volume control system (CVCS) in H^+/B^- form was in service to remove impurities and to avoid as much as possible the formation of the outer corrosion product layer.

Boration and lithium removal were performed within 24 to 48 hours before the end of the first temperature plateau period. At the same time, the hydrogen injection station was stopped, and the coolant environment changed from reducing and alkaline conditions to oxidizing and acidic conditions to clean the component surfaces and to eliminate loose corrosion products. For this purpose, the mixed-bed filter in the CVCS in H^+/B^- form was put into service to remove impurities, corrosion products and also lithium.

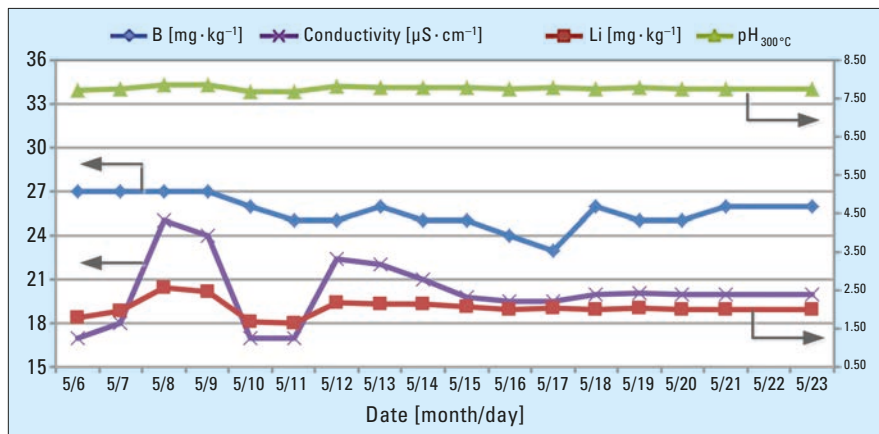


Figure 5:
Boron, lithium, $\text{pH}_{300^\circ\text{C}}$ and specific conductivity during passivation treatment of the RCS.

1) Boron and lithium conditioning during passivation treatment

The trends of boron, lithium, $\text{pH}_{300^\circ\text{C}}$ and specific conductivity during the passivation treatment are shown in Figure 5. All the parameters were stable within the expected range. Maintaining a stable $\text{pH}_{300^\circ\text{C}}$ is especially helpful for the formation of passivation film. In addition, lithium was a major contributor to the conductivity of the coolant.

2) DH control during passivation treatment

DH should be more than $17\text{ mL}\cdot\text{kg}^{-1}$ during the passivation treatment and the expected value is $35\text{ mL}\cdot\text{kg}^{-1}$. The hydrogen station of the CVCS was put into operation when the temperature plateau was reached. Three days later, the hydrogen content reached $17\text{ mL}\cdot\text{kg}^{-1}$ and passivation began. Hydrogen was stable at about $33\text{ mL}\cdot\text{kg}^{-1}$ during the passivation treatment. The hydrogen content in the RCS during the passivation treatment is shown in Figure 6.

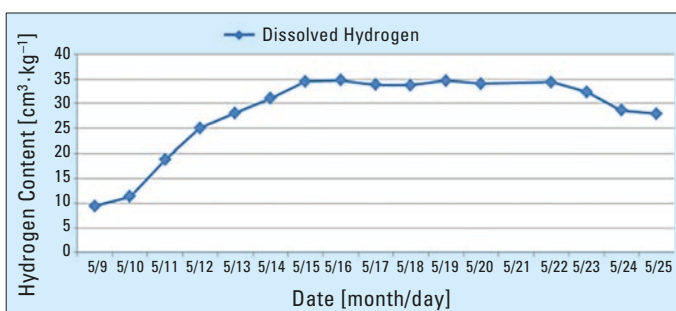


Figure 6:
Hydrogen content in the RCS during passivation treatment.

3) Boration and lithium removal

Cleaning was performed at the end of the passivation treatment to remove the non-protective outer oxide layer generated during HFT to reduce the release of corrosion products during future operation of the unit. Firstly, the lithium was removed to less than $0.03\text{ mg}\cdot\text{kg}^{-1}$ by the

mixed-bed filter in H^+/B^- form in the CVCS. In the meantime, two-step boration was performed to quickly increase the boron content and convert the coolant to a weak acidic environment. The target boron contents for the two boration steps were $1100\text{ mg}\cdot\text{kg}^{-1}$ and $1500\text{ mg}\cdot\text{kg}^{-1}$, respectively, while the real values were $1268\text{ mg}\cdot\text{kg}^{-1}$ and $1549\text{ mg}\cdot\text{kg}^{-1}$.

4) Hydrogen removal

Hydrogen must be removed rapidly during shutdown operation to avoid any risk of the mixing of hydrogen and oxygen during forced oxygenation at or below 120°C . Based on the system configuration, the strategy of hydrogen degassing is as follows: prioritize the operation of the CDS degasser, then use the PZR normal surge line, while increasing the volume control tank nitrogen supply pressure to maintain the CVCS letdown at the maximum flow of $72\text{ t}\cdot\text{h}^{-1}$. If the actions are not effective, feeding and bleeding of water should be considered for further removal of dissolved hydrogen. Chemical dehydrogenation is the ultimate option.

The degasser was put into operation after termination of the passivation treatment, and the hydrogen content decreased within 10 hours to $3\text{ mL}\cdot\text{kg}^{-1}$; this indicates that the degasser was in good condition. The decrease in hydrogen content in the RCS after the passivation treatment is shown in Figure 7.

Water Chemistry Control during Shutdown

Water chemistry control during shutdown includes oxygen removal when the residual heat removal system (RIS/RHR) is connected to the RCS, hydrogen control and forced oxygenation. In the case of forced oxygenation, the dissolved oxygen content of the coolant after hydrogen peroxide injection should be more than $3\text{ mg}\cdot\text{kg}^{-1}$ to ensure thorough oxidation of Ni and Fe in deposits on RCS surfaces.

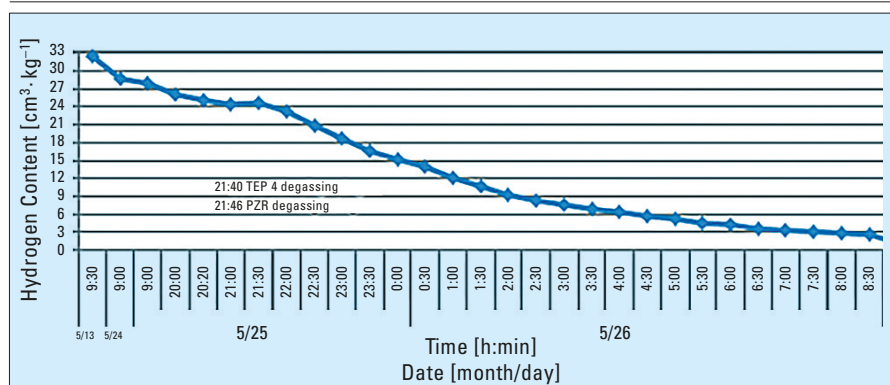


Figure 7:
Hydrogen content in the RCS after termination of the passivation treatment. The decrease in hydrogen content within 10 hours to $3\text{ mL}\cdot\text{kg}^{-1}$ indicates that the degasser was in good condition.

1) Oxygen removal when the RIS/RHR is connected to the RCS

When the temperature decreases to about 120°C, the RIS/RHR is connected to the RCS for residual heat removal. Due to the oxygen saturation in the RIS/RHR, oxygen will enter the RCS and corrode the materials in the primary circuit, especially the stainless steel in the PZR because there the temperature is still above 200°C. Thus, the hydrazine must first be injected into the RCS to remove oxygen during the RIS/RHR connection. The requirement for the oxygen content is less than $100\mu\text{g}\cdot\text{kg}^{-1}$.

During the RIS/RHR connection, the hydrazine was injected into the RCS based on the calculation result. The oxygen content was less than $100\mu\text{g}\cdot\text{kg}^{-1}$ 16 hours later.

2) Forced oxygenation and purification

The chemistry conditions are changed during shutdown operation of the unit from an initially reducing alkaline environment to an oxidizing acidic environment for system cleaning and purification. After boration and lithium removal, nickel and iron slowly increased to about $100\mu\text{g}\cdot\text{kg}^{-1}$, while after hydrogen peroxide injection, the concentration of nickel and iron increased rapidly to about $1100\mu\text{g}\cdot\text{kg}^{-1}$ and $340\mu\text{g}\cdot\text{kg}^{-1}$, respectively. The amount of corrosion products released after adding hydrogen peroxide was lower than expected, which may be due to the absence of crud deposits on the SG tube surfaces.

After hydrogen peroxide injection, the mixed-bed filter of the CVCS was operated at maximum flow rate to purify the coolant.

Impurity Control

High levels of impurities can cause corrosion of reactor coolant system materials and can also affect the formation of the passivation film, especially aggressive impurities such as sodium, chloride, fluoride and sulfate. Therefore, the impurities should be removed to the lowest possible level during HFT. The best ways to remove impurities include feeding and bleeding, and putting the demineralization system into operation.

1) Impurity control in the water/boron make-up system

The process of water make-up to the RCS is as follows: The demineralized water is pumped to the coolant storage system (CSS) and supplied to the primary circuit after degassing. Demineralized water and distilled water of the CSS are monitored periodically to ensure that their qualities meet the requirements of the specification. The results showed that the water qualities of demineralized water and distilled water were stable.

Impurities were at low levels in the boron make-up system during HFT. The silica content was lower than $150\mu\text{g}\cdot\text{kg}^{-1}$; the content of other cations was lower than $50\mu\text{g}\cdot\text{kg}^{-1}$, and that of aggressive anions was stable.

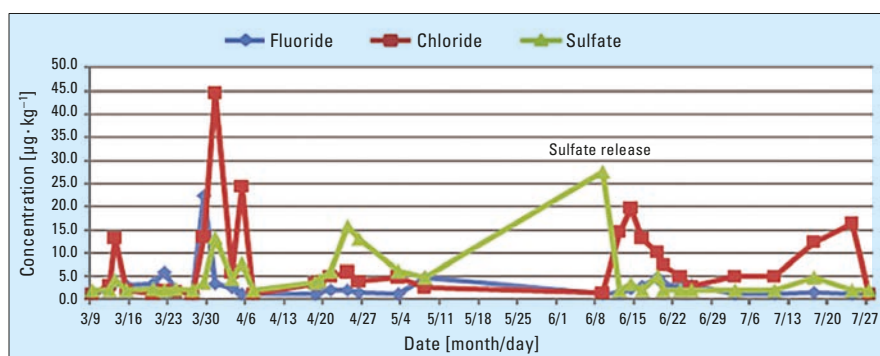


Figure 8:
Aggressive anion concentrations in the RCS during HFT.

2) Aggressive anions in the RCS

Aggressive anions were at low levels during the HFT. Fluoride and chloride increased slightly at the beginning of the startup and heat-up of the RCS, and were removed by the mixed-bed filter of the CVCS. The sulfate concentration increased slightly after hydrazine injection, and may have been released from the cation exchange resins of the CVCS resin. And the release of sulfate during the second startup was higher than that during the first startup; this may have been induced by hydrogen peroxide in the RCS, which was injected in excess for forced oxygenation. The content of aggressive anions is shown in [Figure 8](#).

3) Other ions in the RCS

Corrosion is usually associated with the presence of mineral impurities (such as calcium (Ca), magnesium (Mg) and aluminum (Al)), whereby silica is converted into low soluble compounds (magnesium and calcium silicates, zeolites, etc.) which precipitate on heat transfer surfaces. The main problem is their low thermal conductivity, which limits the heat transfer. They concentrate

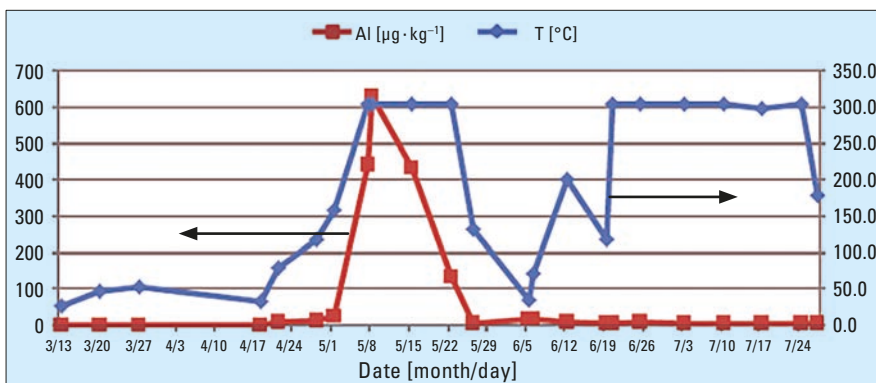


Figure 9:
Aluminum content in the RCS during HFT.

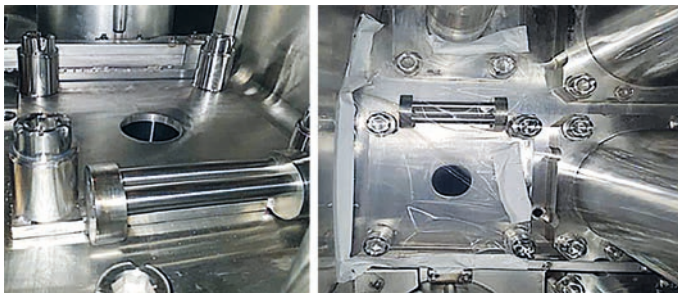


Figure 10:
Photographs and locations of the two SG tube samples.



Figure 11:
Photograph of the coupon after passivation (Inconel 690 TT).

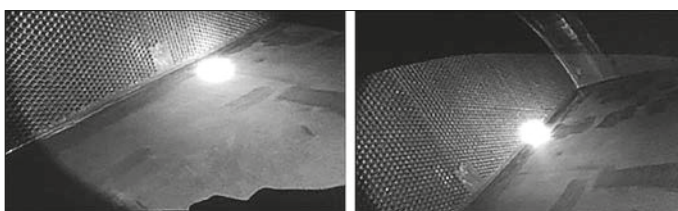


Figure 12:
Photograph of the primary side of the SG.

and precipitate predominantly in the pores between the corrosion product deposits and the zirconia protective layer on the fuel rods. In these areas, the corrosion of zirconium alloys accelerates, in part because of the thermal barrier created by the plugged pores.

The calcium and magnesium concentrations in the RCS were good. Thermal spraying technology was applied on the surfaces of the primary material of the EPR unit. The sprayed material contains aluminum, while the silica comes from

residues in the RCS. Silica and aluminum are released as the coolant temperature rises. The peaks are about $600\mu\text{g}\cdot\text{kg}^{-1}$ and $700\mu\text{g}\cdot\text{kg}^{-1}$, respectively. Since they are difficult to remove by the resin bed, feeding and bleeding of the RCS were performed. The Al content is shown in Figure 9.

Preliminary Evaluation of the Passivation Film

Chemical conditioning during HFT of the EPR unit had been improved compared to other plants. Compliance with the HFT conditioning and procedure guarantees the formation of an optimized oxide layer. Until now no criterion to evaluate the quality of the protective oxide layer has been established. Nevertheless, it was decided to check the results of the passivation treatment after HFT.

Besides performing visual inspection of the material surface of the primary side, two surveillance coupons made of Inconel 690 TT SG tube were installed in the RPV before HFT for evaluation of the passivation film; see Figure 10 [1]. Inspection methods for the surveillance coupons include visual inspection, metallographic analysis, electrochemical analysis and so on, to confirm the effectiveness of water chemistry control during HFT. After HFT, the two coupons were extracted for analysis. To avoid contamination of the coupon surfaces, a steel saw was used to cut them.

1) Visual inspection of the coupons and primary surface

Visual inspection of the coupons showed that the surface was clean. No residual oxide deposits and no corrosion pitting were found, and the film was continuous. See Figure 11. For the status of the primary material surface of the SGs, see Figure 12.

HFT Stages	Purpose	Chemical Actions		Actions Applied to EPRs		Actions Applied to AP 1000s
				Unit 1	Unit 2	
Heat-up	Restrict corrosion by removing dissolved oxygen	Remove the oxygen from the RCS by degassers		√	√	N/A
		Hydrazine injection	With lithium to accelerate the chemical reaction	√	√	
			Without lithium injection			√
Passivation/ pre-oxidation stage: nominal temperature plateau	Reduce corrosion through optimal pH	Lithium injection		√	√	√
	Compensate for lithium effect	Boric acid injection		≈20 ppm	Low content	N/A
	Maintain the reducing condition	Hydrogen injection		Applied but failed to meet the expectations due to low hydrogen station capacity	Applied but failed to meet the expectations due to low hydrogen station capacity	√
	Enhance corrosion resistance Form passive Zn-Cr film	Depleted zinc injection		N/A	√	√
Cleaning phase: at end of nominal temperature plateau	Support nickel and iron dissolution	Remove the lithium		√	√	√
		Boration before temperature decrease		Applied at intermediate shutdown and at the end of the HFT	Applied at the end of the HFT (not applied at intermediate shutdown)	Applied at the end of the HFT (not applied at intermediate shutdown)
	Create oxidation conditions (corrosion product dissolution)	Hydrogen removal		√	√	√
		Hydrogen peroxide injection (T< 80°C)		Applied at intermediate shutdown and at the end of the HFT	Applied at the end of the HFT (not applied at intermediate shutdown)	Applied at the end of the HFT (not applied at intermediate shutdown)

Table 1:
Overview of water chemistry processes during the HFT of EPRs and AP 1000s.

Test Coupons Reactors		Stainless Steel	Inconel 690TT
EPR	Unit 1	N/A	The oxide thickness is 54nm on average with a maximum of 120nm in the inner layer.
	Unit 2	The oxide thickness is around 80nm.	The oxide thickness is around 50 nm.
		⇒ Zinc was detected inside the oxide layer for both coupons. ⇒ Material surfaces were nice.	
AP 1000 [2]		Compared with the base metal, the iron content of the oxides was significantly reduced, while the chrome content was 10 to 30% higher than in the base metal.	Compared with the base metal, the nickel content of the oxides experienced a decrease (primary source of cobalt-58), while the chrome content was 10 to 30% higher than in the base metal.
		The zinc concentration was generally highest on the surface and trended toward a decrease throughout the oxide depth, averaging from 5 to 10% in the oxides.	
Remarks		In the oxide layer formed in both reactors, a duplex structure was observed. The outer surface was rich in Ni and Fe, and the inner layer was rich in Cr.	

Table 2:
Characteristics of the oxide layer during the HFT of EPRs and AP 1000s.

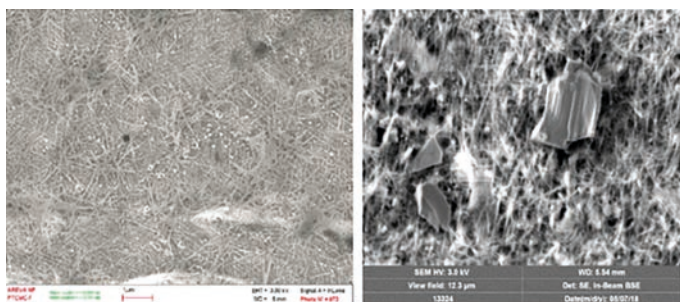


Figure 13:
SEM photographs of the laboratory results (left) and a SG coupon (right).

2) Metallographic analysis and electrochemical analysis of the coupons

The analysis methods include SEM, X-ray, TEM and electrochemical analysis under high pressure and high temperature. The tests are in progress, but the preliminary results can be summarized as follows:

A duplex structure was found for the passivation film. The inner layer was rich in chromium with an average thickness of 54nm and a maximum of 120nm; the outer layer consisted of larger crystals: spinel $Ni_{1-x}Fe_xCr_xO_4$ and/or $Ni_{1-z}Fe_{2+z}O_4$. The cross section was homogeneous, and the grain size of the base metal was about 75μm. In general, the results are similar to the laboratory results and literature data. The results also confirmed that the water chemistry process used in the EPR unit during HFT is suitable. Figure 13 [1] shows the SEM photographs.

Comparison of the Passivation Results with Those of Units Using Zinc Injection during HFT

Besides the HFT of this EPR unit, HFT of another EPR unit in Europe and two AP 1000 units in Asia has been performed with zinc injection during passivation in recent years. A brief summary of the water chemistry processes used during HFT of these units is given in Table 1.

The characteristics of the oxide layers formed during HFT are given in Table 2. It can be seen that, for the test coupons from all four units, even the one using the water chemistry process without zinc injection, better passivation films were formed after HFT, which is fundamental to reducing the radiation source terms during commercial operation of the units. According to the experience feedback of the nuclear industry, zinc injection to the primary circuit should also be beneficial for dose rate control from the perspective of radiation protection. Unfortunately, zinc injection equipment was not foreseen for the first EPR, so this and other advanced water chemistry control technologies, such as maintaining higher and constant pH_T control in the primary coolant, would be available for further reduction of radiation source terms during commercial operation of this and other EPR and AP 1000 units. The benefit of zinc injection for dose rate control should be confirmed by operation of the four units for several fuel cycles, and this is also a good opportunity to compare the dose

rate levels at the units as a function of zinc injection at 3rd generation PWRs.

CONCLUSIONS

As confirmed by the preliminary results obtained from the surveillance coupons in the primary circuit, an excellent passivation film on the component surfaces in the primary circuit could be produced by the application of optimized water chemistry control methods during HFT of the 1st EPR unit. They include tight oxygen control during startup, hydrogen injection and stable $\text{pH}_{300^\circ\text{C}}$ control during passivation treatment, boration and forced oxygenation during shutdown, and stringent impurity control throughout process application. The required treatment time of 300 hours was also sufficient and suitable. The formed passivation film is favorable for corrosion and dose rate control during commercial operation of the 1st EPR unit. Water chemistry control methods during HFT of the other EPR unit and the two AP 1000 units involved additional injection of zinc into the RCS. Operation of the four units over several fuel cycles and a comparison of their dose rate trends should therefore reveal the effect of zinc injection on dose rate control.

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