

Power Cycle Chemistry in Nuclear Cycles: Technology Development and Importance of Fundamental Data

Kenkichi Ishigure

Saitama Institute Technology, Okabe, Saitama 369-0293, Japan
E-mail: ishigure@sit.ac.jp

Operational experience of LWR plants for the past 30 years has shown that water chemistry is one of the most important techniques for the safe and reliable operation of the plants. Extensive developments of the technology have been made over the world for the past decades and now provide the various kinds of technical options. Active researches and developments have been carried out also in Japan, and many technical options have already been applied to actual plants. This paper describes the current status of the technology mainly in Japan and then points out the importance of the integrated research programs and the needs of the fundamental data for supporting the technology.

1. Introduction

In the 1970's when operational experience has not much accumulated, a large number of LWR plants over the world suffered from many serious troubles of various types owing to the insufficient control of water chemistry in coolant systems. Thus, water chemistry of coolant systems has been widely recognized to be of vital importance for the safe and reliable operation of nuclear power plants. Water chemistry is a technology to control water coolant chemically in the optimum condition, and its targets are considered to be as follows:

1. reduction of radiation sources causing occupational radiation exposures,
2. integrity of structural materials,
3. integrity of fuel cladding,
4. reduction of radioactive wastes.

The relative importance of each target has changed from time to time, depending on the operational situations of plants.

Extensive efforts have been devoted to research and developments in various fields of water chemistry for the past decades, and now the water chemistry technology has been highly developed and widely diversified. This paper gives a brief review on the recent status of the technology and the research activities in this field with the main emphasis on the Japanese situations and then describes the needs of fundamental data to support and optimize the technology.

2. Current Status of Water Chemistry Technology

As already described, in the 1970's many water cooled reactors experienced various types of troubles that included very high levels of occupational radiation exposures, intergranular stress corrosion cracking (IGSCC) of stainless steel piping in BWR and corrosion troubles of steam generators in PWR. This stimulated active researches in this field to develop countermeasures against these troubles. Hence, water chemistry technology started as a trouble-shooting technology. Very active R&D in this field for more than 20 years has provided a large variety of technical options to solve and prevent these problems. The introduction of the highly developed technology have improved dramatically the situations of Japanese plants, and demonstrated that water chemistry is very effective to achieve the above four targets. For instance, the occupational radiation exposures have remarkably reduced in the 1980's with Japanese BWRs through the adoption of the technical options developed as shown later, and they attained the top class performance in the world.

After finishing the trouble-shooting, water chemistry technology is now required to predict and prevent troubles that may happen in the future. Thus, the technology should be predictive and preventive. Since each technical option is usually specific to one of the targets, and is not almighty to

all of them, it is essential to make optimization among the various technical options available.

There are two current issues of concern in relation to the operation of LWR from the viewpoint of water chemistry. One is the higher performance operation of plant that includes the increase in the burn-up and linear power out-put density of nuclear fuels, the longer cycle of operation etc. and the other is "plant aging" problem. The burn-up of LWR fuels is going to be increased to 60,000 mega watt · day/ton (MWd/t) or higher step by step in Japan. The increase in the burn-up together with the higher performance operation is anticipated to give a big impact not only to the performance of the fuels, especially to the corrosion of the fuel cladding but also may affect the activity transport processes such as the deposition of corrosion products on fuel surfaces through sub-cooled nucleate boiling in PWR. One of the recent related concerns is anomalous crud deposition and/or axial offset anomaly (AOA).

Plant aging is now one of the most important problems for the safe and reliable operation of LWR. Among others, irradiation assisted stress corrosion cracking (IASCC) of in-core materials is a key issue especially in BWR. It is well-known that the overlapping of three factors, that is, material, stress and environment, is required for IGSCC to take place, and in the case of IASCC, all of the factors may be affected by irradiation. Water chemistry is expected to provide preventive measures against IASCC as technical options.

Originally, water chemistry control of coolant has been performed for many years on the basis of the different concepts between PWR and BWR. In PWR water chemistry has been controlled with the additives not only for the primary side but also for the secondary side. The control of pH and the elimination of dissolved oxygen in the systems are major targets. On the other hand, in the case of BWR, the increase in the purity of coolant water has long been the most important way to control the water chemistry and, therefore, "purer is better" (ref. 1). Recently, however, this principle has been subjected to modification, and the addition of a small amount of chemicals to coolant has been important to control the water chemistry of BWR as described later. A brief review of the technical options available is given below for water chemistry of PWR and BWR.

2·1. PWR

Primary coolant of western PWR is chemically controlled with the addition of boric acid, lithium hydroxide and hydrogen. Boron is added as a chemical shim for neutron control, and lithium is used to control pH of the system in the range favorable against the corrosion of structural materials. Hydrogen is added to suppress the formation of oxidizing species from the radiolysis of water coolant.

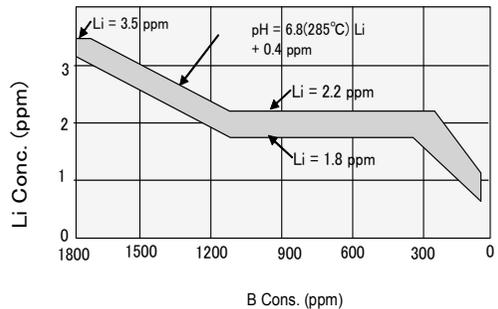


Fig. 1. Scheme for the pH control recommended in Japan.

The concentrations of those additives in reactor water had been controlled for many years to be appropriate in the ranges determined by technical specifications, but the more strict management of pH was recognized to be very important for the control of the activity transport. Now in Japan it is recommended to take the elaborate scheme of pH, depending on the operation cycle of plants, as shown in Fig. 1 (ref. 2).

The increase in fuel burn-up requires the higher concentration of boron at the early stage in the operation cycle of a plant, which leads to the corresponding decrease in pH, since the concentration of lithium has the upper limit to suppress the corrosion of fuel cladding. To overcome this dilemma it is proposed to use boric acid enriched with ^{10}B instead of natural one.

Recently there has been a growing interest in revising the specification of hydrogen level in primary system to look for the possibility of its reduction because of potential adverse effect of hydrogen on primary water stress corrosion cracking (PWSCC) of steam generator tubing and because of the probable reduction of radiation fields. The minimum requirement of the hydrogen level was determined many years ago based on the experimental results obtained at ambient temperature and is considered to include much

redundancy coming from the conservative evaluation.

As will be described later, zinc injection to reactor water is now applied to many BWRs in U.S.A. for the reduction of radiation fields. This technical option is drawing attention from PWR side and considered to be probably effective also in PWR. There are test programs to show that the zinc injection is effectively applicable to PWR with no adverse effects on the corrosions of structural materials and fuel cladding.

Steam generators of PWR over the world have suffered from several types of serious corrosion troubles mostly owing to the insufficient control of water chemistry in the secondary side. Steam generators (SG) composed of mill annealed (MA) 600 alloy tubing were finally replaced with SGs having alloy 690 tubing in many old plants in Japan and other countries. The secondary side water chemistry has been controlled with the addition of hydrazine and ammonia to the coolant. The latter is used to control pH of the secondary system, but its evaporation caused by boiling in SG brings about the decrease in pH and the unfavorable condition for corrosions including flow assisted corrosion (FAC) outside SG, leading to the increase in the corrosion product input into SG. One of the remedial actions against this is to increase the concentrations of hydrazine and ammonia, but as another technical option ammonia is partly replaced in many plants with volatile organic amines like ethanol amine (ETA), morpholine etc. In some of Japanese PWRs ETA is selected and now added to the secondary side coolant.

The current concern is the deposition of corrosion products, mainly magnetite, on the surface of SG tubing in the secondary side, even in replaced SGs. There is also increasing interest in the application of chemical cleaning to some Japanese PWRs to remove deposited corrosion products in SG (ref. 4).

2.2. BWR

Many of BWRs over the world experienced two big troubles; one is IGSCC of stainless steel piping in re-circulation line etc. and the other the high occupational radiation exposures. These two troubles have been overcome by the various countermeasures not only from water chemistry but also from materials and others, but the contribution of water chemistry was very large and important.

The environmental factor, one of the three requirements for IGSCC of stainless steel in BWR, comes mainly from oxidizing species such as oxygen and hydrogen peroxide produced by the radiolysis of water in reactor core. Addition of hydrogen in reactor water suppresses the formations of these oxidizing species. This technical option is already adopted in PWR, but not originally in BWR because boiling of water in core was considered to reduce its effectiveness owing to the stripping of hydrogen to vapor phase. It was found, however, that in some locations like re-circulation line, hydrogen addition does suppress effectively the production of oxidizing species by radiolysis even with the boiling in reactor core. Therefore, many BWR plants in U.S.A. and Sweden, adopted hydrogen water chemistry (HWC) as a preventive measure against IGSCC of stainless steel, but its addition concentration was limited to relatively low level because of the increase in radiation dose rates around turbines due to ^{16}N . Japanese plants, however, have not introduced HWC until recently but adopted the other option, that is, the material replacement. Thus, 304 stainless steel piping has been replaced by that of 316L type in many plants. However, the current generation of IGSCC and/or IASCC of in-core materials, even of 316L stainless steel, brought about new situations in Japan.

HWC is by itself not a sufficient countermeasure against IASCC of in-core materials. Recently noble metal chemical addition (NMCA) was proposed as a booster to increase the effectiveness of HWC even at low concentrations of hydrogen (ref. 5). There are now an increasing number of BWR plants that have adopted NMCA together with HWC in U.S.A., but so far not many in Japan. Some of Japanese aged BWRs have replaced their core shrouds with new ones as a countermeasure against IGSCC and/or IASCC.

The control of crud or insoluble corrosion products in reactor water has been recognized in the early days to be of vital importance for the reduction of radioactivity accumulation on the surface of piping in BWR. The key target of the crud control is the reduction of iron input into reactor core from feedwater system. This target was attained in Japan by the control of dissolved oxygen in feedwater, the improvement of condensate demineralizer system, and the replacement of materials. In consequence, iron levels in feedwater were successfully reduced to sub-ppb levels in some plants. This marked reduction of iron input

accompanied the relative increases in nickel concentration and, subsequently, ^{58}Co activity in reactor water. Thus, not only the control of iron concentration but also of Ni/Fe ratio was considered to be important for keeping the low levels of activities in reactor water (ref. 6). The Ni/Fe ratio control was effective to attain the low levels of activities in reactor water of some plants, while it was not so in others where new fuel assemblies with different treatment of fuel cladding had been introduced. These situations led to the invention of ultra-low crud and high nickel control which was applied effectively to plants with dual condensate demineralizer using hollow fiber filters (HFF) (ref. 7).

Zinc injection to reactor water is now widely applied to BWRs in U.S.A., some of which employ depleted zinc instead of natural one to suppress the contribution of ^{65}Zn to radiation field. In contrast, there are a few plants in Japan that have adopted zinc injection as a technical option for the control of radiation field.

Twenty years ago the reduction of occupational radiation exposures was a very strong incentive to achieve with Japanese BWRs. As described previously, the situations have been dramatically improved until 1990 and the radiation exposures in Japanese BWRs have been reduced to the lowest levels in the world. This has made them lose the motivation for the further effort to reduce the radiation exposures for the past 10 years. The recent record, however, shows that the situations have changed again and that Japan has fallen to the relatively worse levels of occupational radiation exposures not only with BWR but also with PWR. This situation now makes us pay attention again to the reduction of radiation exposures in Japanese plants.

3. R&D Program

Water chemistry is a technology dealing with very complicated phenomena related to the interactions of water environment with materials. For instance, the activity transport involves many processes in and out of core of plants, and the technology is usually developed step by step based on operational experience and scientific understanding. In the process of the technology development basic laboratory experiments are followed by out-of-pile loop tests, and then integrated tests are performed using in-pile loops of research reactors. The integrated tests are very

important to confirm and optimize the technical option under the real conditions of reactors, and are sometimes executed in Japan as large programs, for instance, national ones. Eventually the verification is performed in actual plants. Here some examples are shown for such integrated tests together with the supporting experiments carried out in Japan. Finally it is stressed that the fundamental data are necessary and important to support the technology, and some examples are shown below.

3.1. PWR

It is already described that pH control is of vital importance for the reduction of radiation fields in PWR. An integrated program was carried out in 1989-1995 in Japan to verify the effectiveness of higher pH for radiation reduction (ref. 4). In this program irradiation tests were carried out using simulated PWR loops set up in a research reactor to compare the effect of pH on the activity build-up on the surfaces of the simulated loop materials such as inconel, zircaloy, and stainless steel. The comparison of the test results clearly showed that the increase in pH decreased the activities deposited, for instance, on the surface of the inconel part. Besides the in-pile loop experiments described above, material tests using SRRT method were carried out using out-of-pile loops to confirm the integrity of component materials under the various conditions of modified water chemistry. In Fig. 2 are shown contour lines for the fraction of the intergranular fracture of MA 600 inconel coupons under various conditions. The results indicate that high pH does not necessarily provide the more aggressive environment to IGSCC of inconel material in the presence of boron.

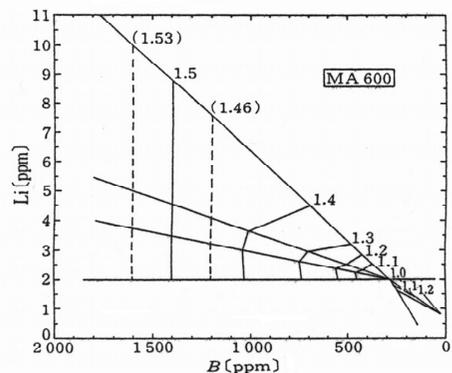


Fig. 2. Effect of concentrations of B and Li on IGSCC of MA600. Lines are contour lines expressing relative susceptibility of IGSCC.

In the years of 1995-2002, another similar test program was carried out on zinc injection (ref. 8), using simulated PWR loops built in a research reactor. Features of this program are the post irradiation examination (PIE) of the loops themselves and computer simulations performed for the more generic analyses on the basis of the PIE results together with those of the out-of-pile experiments. The test result indicated that the addition of 10 ppb zinc reduced ^{60}Co accumulations on the surfaces of inonel, and that the reduction of the Co accumulation by the Zn addition arose mainly from the decrease of Co in the inner layer of the surface oxides, as shown in Fig. 3. In this zinc program some elemental tests using out-of-pile loops were included to elucidate the behavior of zinc and to understand the mechanism not only under PWR condition but also under BWR one. Similar results were obtained from the out-of-pile

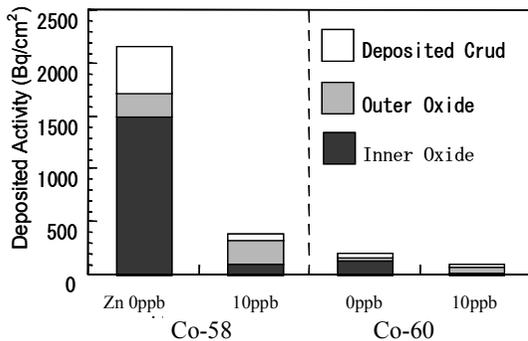


Fig. 3. Co activities deposited on inonel surfaces under PWR condition in the systems with and without Zn.

experiments to support the effectiveness of zinc injection in PWR.

In Fig. 4 are compared the depth profiles of oxide layers formed on the surface of stainless steel with and without zinc addition. Glow discharge spectroscopy (GDS) was used for the measurement of the depth profiles in the experiments. It is well-known that the oxide layer formed on the surface of stainless steel in high temperature water comprises double layers, and this is clearly seen in the figure of the sample without Zn. The figure also shows that the added zinc is picked up much more in the inner layer than in the outer layer with the affinity to Cr in the layer.

The optimization of the hydrogen level in primary coolant remains to be solved. Computer simulation shows that the minimum hydrogen level required is much lower than the present specification. The higher performance operation of PWR, however, permits the thermal hydraulics in core to include sub-cooled nucleate boiling of coolant, which has a possibility to change the local water chemistry that might lead to severe fuel corrosions and other anomalies, especially at high burn-up. Therefore, careful preparation may be required with detailed tests to verify the integrity of materials and fuels as well as the merits of lowering the hydrogen concentration.

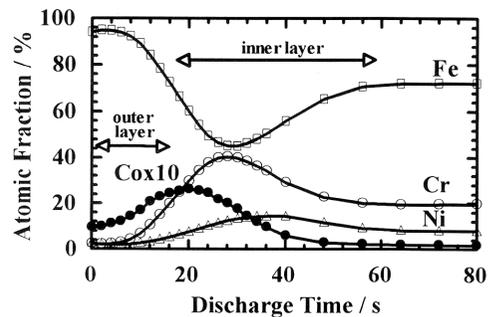


Fig. 4 a. GDS depth profile of stainless steel DO=0,Z=0 ppb, 1000 h, 288 °C.

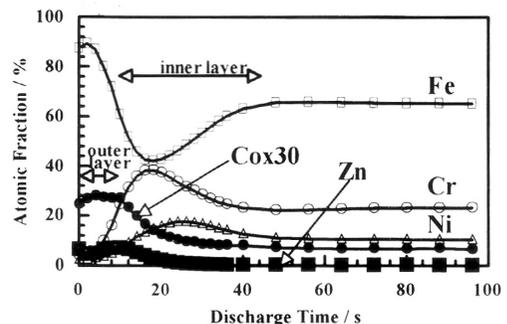


Fig. 4 b. GDS depth profile of stainless steel DH=100 ppb, Zn=10 ppb, 1000 h, 288 °C.

3.2 BWR

HWC is one of the useful measures against the IGSCC and/or IASCC, the major aging problem of BWR, but the injection of hydrogen is limited to the lower levels and insufficient to suppress fully the production of the oxidizing species in core. Thus, it is a large concern how far the added hydrogen is effective to reduce the concentrations of the oxidizing species in core. In this regard

electrochemical corrosion potential (ECP) of stainless steel is an important index for the quantitative expression of the aggressiveness of the environment to IGSCC. It is recognized that IGSCC of stainless steel is not generated when ECP is lower than a threshold value, -230 mV, at about 280 °C. Trials were made to measure ECP of stainless steel in core of some Japanese BWRs, but the results were not so reliable and look to be inconclusive. The reference electrodes used for the measurements in core did not work for a long time but broke down during the measurements. Therefore, recently the ECP measurements have been carried out in the bottom drain line of BWR, but the results give the information only about the limited location.

The ECP measurement in core of actual plants is technically difficult and is unable to be carried out at many locations in reactors. Therefore, the evaluation of ECP in core by calculation is expected to give more information and support the measured results. The procedure for the calculation of ECP was already established (ref. 4).

The final target of the calculation is to evaluate the propagation rates of cracks generated under usual BWR and HWC conditions. An evaluation model combined with the radiolysis and ECP calculations was already proposed (ref. 6). The more experimental information is required on the chemistry inside the relevant crevices or cracks for the calculation using this type of models.

Recently more and more attention has been paid to NMCA as the booster to HWC. It has been verified that NMCA is very effective to reduce the ECP values of stainless steel with the lower concentrations of hydrogen added. The chemical behavior of the added noble metals is, however, not understood well and there is some concern on its effects on the activity transport processes and on the corrosion of fuel cladding. More researches are needed to make clear the chemical behavior of noble metals in high-temperature water and the surface of stainless steel.

IASCC of in-core materials includes very complicated phenomena, because radiation in core may affect the factors of the material, environment, and probably stress. It is very important to elucidate the roles of radiation in IASCC, but in many of the past research programs of IASCC, the SCC tests of irradiated material coupons were carried out under out-of-pile conditions without radiation where synergetic effects of radiation, if any, on the SCC factors are missing and unable to be studied. There

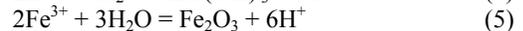
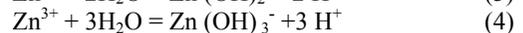
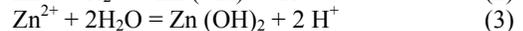
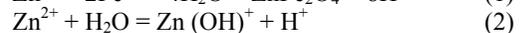
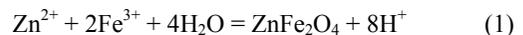
started a six-year research program in Japan in order to study the synergetic effect of radiation in IASCC (ref. 11). In this program stainless steel specimens are irradiated to various neutron doses in a high temperature water loop in a research reactor and then post-irradiation SCC tests are performed under both in-pile and out-of-pile conditions for comparison. In-core monitoring techniques are essential in the in-pile SCC tests and are to be developed in the first phase of this program.

3.3 Importance of Fundamental Data

As already described, it is very important to make optimization of technical options in case of their choice in a plant. Since the optimization is sometimes specific to the plant and its life cycle, basic understanding of the technical options is essential to make decision. Thus fundamental data with high reliability are required and should be consolidated.

It is widely known that the strict control of pH in the primary system was originally introduced based on the solubility data of magnetite (Fe_3O_4) under PWR condition and the calculation of solubility was shown to be possible on the basis of equilibrium if the thermodynamic data are available (ref. 12). Thermodynamic calculation of spinel solubility is more complicated under the BWR conditions compared with the PWR where the pH of the system is approximately determined by the additives.

Zinc ferrite (ZnFe_2O_4) is one of key materials in relation to zinc injection and its solubility calculation under the BWR conditions is shown as an example (ref. 13). The reactions involved are:



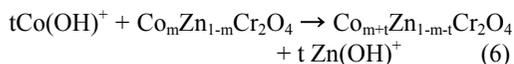
Concentrations of soluble zinc and ferric species in an equilibrium with zinc ferrite are determined by eqs. (1) and (5) according to the thermodynamic stability evaluation, which predicts that the system with the deposition of Fe_2O_3 is more stable than the system without it. Zinc ions react with water molecules according to eqs. (2)-(4). Equilibrium constants of these reactions called hydrolysis constants of metallic ions are indispensable to these

calculations but their reliable data at high temperatures are rather poor.

The equilibrium constants for equations (1) and (5) can be calculated from the Gibbs free energies of formation of the relevant compounds, among which the data are poorly available for aqueous ions, though empirical methods are proposed to evaluate the values in high temperature water (refs. 14 and 15). The related problem is the accuracy of the formation Gibbs free energies for spinels. Generally, the values for those complex solid compounds are larger than those for simple molecules like water and aqueous ions involved in the reactions. Consequently, a small error, for instance, 0.1% , for the values of these spinels gives much greater impact to the calculation results in comparison with those of simple compounds and ions.

In the example shown above only a simple spinel is considered for the calculation, but the situations are more complicated in the real systems where non-stoichiometric mixed spinels as $Ni_mFe_{1-m}Fe_2O_4$ are major components in stead of simple spinels. Thermodynamic data are missing with non-stoichiometric mixed spinels and are required to evaluate from the data of the simple component spinels. A simple evaluation method is proposed (ref.16) to calculate the Gibbs free energies of formation of mixed spinels using site preference energy of spinels and configurational entropy of mixing. Recently a more sophisticated model is proposed (ref.17) in which configurational and non-configurational Gibbs energy contributions are taken into account using “regular” approximation for cation interactions. In the application of this model, the data are required for parameter W_{ij} representing the interaction energy between cations i and j in the sub-lattice of a spinel.

It is possible to consider the mechanism of Zn action to suppress the pick-up of cobalt into the oxide layers on the surface of stainless steel using thermodynamic data (ref. 18). It is assumed that the cobalt ion in reactor water is picked up into oxide layer comprising a mixed spinel by the equation,



Here for simplicity metal ions M^{2+} are assumed to take the form of $M(OH)^+$ in the aqueous phase. If eq (6) is thermodynamically favorable to go forward, the cobalt ion is trapped into the solid phase with the release of zinc ion to the aqueous

phase. Conversely, if eq (6) favorably goes backward on the thermodynamic basis, the cobalt ion is released to the aqueous phase while zinc ion goes into the oxide phase. Thus, the cobalt and zinc ions in aqueous phase are competing to each other to get into the solid spinel phase. On the basis of this assumption, the thermodynamic stability of eq (6) is a key factor to determine whether the zinc ion in the aqueous phase to suppress the pick-up of the cobalt ion into the solid phase. The data of Gibbs free energies of formation for mixed spinels $\Delta_f G(Co_mZn_{1-m}Cr_2O_4)$, are required to evaluate the thermodynamic stability. The consideration of the mass balance of the system gives rather simple criteria as follows:

$$q/p > \exp \{-I(m)/RT\} \quad (7)$$

$$I(m) = d/dm [\Delta_f G(Co_mZn_{1-m}Cr_2O_4)] \quad (8)$$

Here q and p express the concentrations of zinc and cobalt in the aqueous phase, respectively, and $I(m)$ is given by eq (8). If eq (7) holds, the zinc ion in the aqueous phase drives reaction (6) to the left side and consequently suppresses the cobalt pick-up.

If $\Delta_f G(Co_mZn_{1-m}Cr_2O_4)$ is calculated by the simple model based on site preference energy of metal ions in lattice (ref. 16), the values of $\exp[-I(m)/RT]$ are easily calculated as a function of m as shown in Table 1. The result predicts that in case of the chromite spinel zinc ion of ppb level suppresses the pick-up of cobalt ion of ppt level in the aqueous phase, accompanying the cobalt release from the oxide layer. This seems to be consistent with the experimental results and plant data.

Another example is related to the evaluation of ECP for stainless steel of in-core material. The procedure of ECP evaluation is composed of three steps, radiolysis analysis, ECP calculation, and the

Table 1. Threshold values of $[ZnOH^+]/[CoOH^+]$ for Co pick-up by $Co_mZn_{1-m}Cr_2O_4$.

m	$\exp [-I(m) / RT]$
	$Co_mZn_{1-m}Cr_2O_4$
0.03	326
0.05	189
0.11	78
0.21	37

evaluation of crack propagation rate. This requires the other types of fundamental data.

First, the radiolysis reactions of high temperature water is analyzed by numerical calculation, for which the yields (free energy G values) of the primary species produced by γ -rays and fast neutrons and the rate constants of the relevant reactions (about 40) are required as input parameters. Then the values of ECP are evaluated according to mixed potential model using the results of the radiolysis calculations. For the latter process are required anodic polarization curves of stainless steel in pure water at the high temperature and some electrochemical parameters like exchange current densities of the cathodic and anodic reactions on the surface of stainless steel.

Vigorous discussion has been made on the methodology and the reliability of the calculations of radiolysis and ECP (ref. 19). The principle of the radiolysis modeling is very clear and simple. There are still some ambiguities in the radiolysis data used as the input parameters, though the extensive researches have made a large contribution to provide the more reliable data base. Moreover, boiling of water in core and flow dynamics of the coolant in reactor make the modeling more complicated and more difficult. Further information is needed on these points to makes the radiolysis calculation more reliable.

The calculation of ECP also includes some ambiguities on the anodic polarization curves of stainless steel and the electrochemical parameters of the cathodic and anodic reactions used as the input data such as the exchange current and limiting current densities especially for hydrogen peroxide. In these electrochemical processes, oxide layers formed on stainless steel are considered to play an important role, but the present models do not take them into account explicitly. It is necessary for establishing the calculation procedure to make more systematic comparison between ECP values calculated and measured under various conditions of water chemistry.

4. Conclusions

Water chemistry deals with the very complicated phenomena on the interactions of structural materials and fuels with water environment under irradiation and it is a technology to control the interactions from water side. Basic understanding with the relevant fundamental data are need for a further advance of the technology.

It is understood well that there are oxide layers at the interface between water environment and metallic materials, playing the decisive roles in the interactions between them, and it may be said that the water chemistry control is the control of the interfacial oxide layers from the water side. Nevertheless, their roles are not well understood, being sometimes phenomenological, qualitative and even neglected. Deeper understanding is needed on formations, structures, properties, surface reactions etc. of the interfacial oxide films.

Local chemistry inside cracks or crevices is sometimes largely different from bulk chemistry, but is very difficult to measure directly. Usually it is evaluated by simulation or model experiments. More information on crack chemistry is needed for the quantitative evaluations of crack propagations or some other local corrosions.

In situ monitoring techniques, for example, pH or ECP monitoring, are very important but rather difficult, especially in core. They are expected to work as key technologies for preventive and predictive measures the plant aging and also to deepen the understandings of the phenomena.

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