

Effects of Dissolved Hydrogen Content in PWR Primary Water on PWSCC Initiation Property

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ABSTRACT

Environmental mitigation is being looked forward to as one of the promising preventive measures for better plant maintenance. Especially, it would be much more effective, when environmental measures are introduced in combination with mechanical measures, such as stress improvement, material replacement, and so on.

Dissolved hydrogen (DH) concentration in the primary cooling system has been controlled at the level of 25~35 ml STP/kg H₂O in all PWR plants in Japan, maintaining a sufficient margin to the utilities' self-regulated band 15~50 ml STP/kg H₂O. The lower limit of this self-regulated band was determined to suppress reactor coolant radiolysis based on experiments using a test reactor over 50 years ago, though the test was performed at much lower than typical operational temperature and is considered over-conservative at present.

On the other hand, primary water stress corrosion cracking (PWSCC) events have occurred on Dissimilar Metal Welds (DMW) at vessel nozzles or at vessel head penetration in some PWR plants in Japan in recent years. PWSCC growth test data have been showing that the current management band of DH content is around the peak of crack growth rate (CGR) at about 340°C, corresponding to the operating temperature of the pressurizer. To avoid the higher CGR levels, the DH content band should be shifted to the higher side, or to the lower side. The authors suggest much lower DH content than that at present as an alternative control, since some experimental data on PWSCC initiation show monotonically decreasing dependency of initiation time with increasing DH content.

In this paper, we show the effects of DH content on PWSCC initiation property. Reverse-u-bend (RUB) tests and three-point-bend (3PB) tests were conducted for Alloy 600 base metal and Alloy 182, respectively, to examine the dependency of the lower DH content than currently controlled band on PWSCC initiation time. Test results showed the advantage of lowering DH content down to around 5 ml STP/kg H₂O compared to 15~25 ml STP/kg H₂O. Analyses results of oxide and deposits on the surface of the test specimens were also shown to try to clarify how hydrogen interacts with nickel-base alloys and influences the propensity to PWSCC. Based on the analyses results of surface oxide and deposits, an outline of the interface region was drawn at low and intermediate to high DH content.

Current status of the total studies on DH optimization and challenges left were summarized.

KEYWORDS

Environmental Mitigation, Dissolved Hydrogen, PWSCC

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1. Introduction

Environmental mitigation is considered to be one of the effective preventive measures against stress corrosion cracking (SCC) in nuclear power plants (NPP). Although development of more corrosion-resistant material and stress improvement such as peening are also effective preventive measures for SCC, the effect of those mechanical preventive measures is limited to the position of the components where those measures are applied. Environmental mitigation affects much broader areas of the system to which it is applied than do mechanical measures. Moreover, the

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environmental mitigation costs much less than mechanical measures in most cases. We could reap a great deal of merit if we were to introduce environmental mitigation in combination with the mechanical preventive measures. For example, hydrogen water chemistry (HWC), noble metal chemical addition (NMCA) and so on have been developed and applied to many BWR plants all over the world, in combination with stress improvement like water jet peening.

Recently there have been many examples of PWSCC on dissimilar metal welds (DMW) of Vessel Head Penetration and Vessel Nozzles. Repairs such as weld inlay, or spool piece replacement have been applied to the damaged DMW, using Alloy 690 for repair/replacement as a PWSCC-resistant material. Stress improvement such as ultrasonic shot peening (USP) and laser stress improvement process (L-SIP) are applied. However, environmental mitigative measures for PWSCC are under development.

Dissolved hydrogen (DH) concentration in PWR primary water has been controlled sufficiently to suppress the reactor water radiolysis to prevent structural material from SCC due to the oxidizing species generated by water radiolysis. The lower limit of current utilities' self-regulated band of DH content, 15ml STP/kgH₂O, was established based on the results of Hart's experiment in the 1950's [1] from the viewpoint of suppressing the oxidizing species such as Hydrogen Peroxide (H₂O₂). However, this experiment was carried out under the temperature condition of 60°C, which was much lower than the actual operating temperature in a real plant. It is expected that re-combination of oxidizing species with hydrogen becomes more dominant than the generation of oxidizing species at higher operating temperature resulting in a well-suppressed condition of oxidizing species even with a smaller amount of DH content than that necessary at 60°C. To examine the suppression effect of water radiolysis by DH in high temperatures occurring during operation quantitatively, a calculation of critical hydrogen concentration (CHC), which is defined as the minimum necessary DH content to suppress the oxidizing species concentration below 50% increase compared to a saturated value assuming infinite DH supply, was performed using a radiolysis computing model developed by Studsvik Nuclear AB. The calculation result supported the expectation that the current lower limit of self-regulated band of DH content was too conservative [2]. To confirm the calculation results in a real plant, electrochemical corrosion potential (ECP) was measured in Tsuruga Unit 2, changing the DH content within the range of the self-regulated band. The measurement results of ECP supported the calculation results of water radiolysis [3].

Some reports say that the experimental data of PWSCC growth rate has a convex upward dependency for DH content, that is, CGR peaks around a DH content position, which depends on temperatures tested [4][5][6][7]. According to those reports, for example, the current management band of DH content in Japan, 25~35ml STP/kg H₂O, causes peak CGR at just around 340°C, which is the operating temperature of the pressurizer. This CGR dependency on DH content suggests to us the current management band of DH content is in the worst position from the viewpoint of PWSCC propagation. Since CGR dependency on DH content has a peak, it is possible for us to select two different orientations for improvement. One is moving to higher DH content, and the other possibility is moving to lower DH content.

On the other hand, it is reported that the experimental data of PWSCC initiation shows a monotonic decrease of initiation time for the increasing DH content [8][9][10]. From the utilities' point of view, improvement of PWSCC initiation resistance yields more advantages than that of propagation resistance only. Because most of DMW has relatively higher weld residual stresses in the circumferential direction than in the axial direction, the crack tends to grow in the axial direction without stationary tendency and will penetrate sooner or later. Therefore, it is necessary for the utilities to perform successive inspections frequently. It would be better for us utilities to have a perspective on PWSCC initiation possibility in the operating period, so that we could prepare preventive measures or repair/replacement activities in a more proactive manner. This is the major reason why the authors consider an orientation for lower DH content more promising. Data and discussion on the effects of DH content on PWSCC initiation property are given in section 2 in detail.

Influences of lowering DH content on PWSCC growth, the structural integrity of the other materials and the other degradation modes such as IASCC or IGSCC of stainless steels, fuel integrity and the source of radiation dose must be taken into account. Current status and challenges are briefly summarized in section 3.

2. Effects of DH Content on PWSCC Initiation Property

2.1 PWSCC Initiation Tests

To investigate the influence of DH content on PWSCC initiation property of nickel-based alloys, long-term constant load tests in simulated PWR primary water have been carried out. Test temperature was set at 320°C which is identical to reactor coolant outlet temperature in a PWR, without acceleration in temperature of SCC susceptibility.

According to the previous studies, crack initiation time of Alloy 600MA increased significantly at lower DH levels, from the results up to about 9,000 hours of exposure [9]. In this study, the latest test results for over 25,000 hours of exposure were obtained [11]. The characterization of oxides and deposits formed on test specimens tested in the 15ml STP/kgH₂O condition, assumed to be close to the Ni/NiO phase boundary, has been investigated to discuss possible mechanisms for PWSCC initiation.

The crack initiation time for Alloy 600 was evaluated using RUB specimens made from 3/4" and 7/8" 600MA tube and from 3/4" 600TT tube. Surface finish condition of RUB specimens was as same as that of real tubes. The stress in the axial direction (σ_1) of the 7/8" RUB specimen was about 700MPa, and the stress in the perpendicular direction (σ_2) was about 530MPa. For the 3/4" RUB specimen, σ_1 and σ_2 were about 570MPa and 440MPa, respectively.

The Alloy 182 has not been tested for crack initiation before, although it has been shown to be susceptible to PWSCC growth. Because of the difficulty in applying the RUB specimen as the weld metal, the 3PB specimen was chosen for Alloy 182. Surface of 3PB specimens were ground and polished, to remove the very thin layer due to EDM cutting, taking care not to introduce a work-hardened layer. 3PB specimens were loaded up to the yield stress at room temperature, according to the standards SS-ISO-7539-2 or ASTM G39. 1.25 and 1.5 times deflection of the first case were also loaded. Table 1 shows the number of each type of specimen in each autoclave in detail.

Three different DH content levels were selected to watch DH dependency on initiation time, that is, 25, 15 and 5ml STP/kgH₂O. As shown in Table 2, a separate autoclave was used for each condition of DH content. 12 RUB and 24 3PB specimens were put in each autoclave. Chemical composition of test materials and the schematic of RUB and 3PB specimens were shown in literature [11].

Table 1 Test Specimen Types and the Number of Specimens for Each Autoclave [11]

Material of Test Specimen			Autoclave 1	Autoclave 2	Autoclave 3
Alloy 600MA	3/4"	RUB*	5 specimens	5	5
Alloy 600TT	3/4"	RUB	5	5	5
Alloy 600MA	7/8"	RUB	2	2	2
Alloy 182	$\Delta \rightarrow (\sigma = R_p 0.2)$	3PB**	8	8	8
Alloy 182	1.25 Δ	3PB	8	8	8
Alloy 182	1.50 Δ	3PB	8	8	8

*RUB: Reverse-U-Bend

**3PB: Three-Point-Bend

Table 2 Water Conditions of Each Autoclave Tested [11]

Parameter	Autoclave 1	Autoclave 2	Autoclave 3
Dissolved Hydrogen (cm ³ STP/kgH ₂ O)	25	15	5
Temperature (degree C)	320		
Pressure (MPa)	15.2		
Conductivity (μ S/cm)	21		
Boron (ppm)	1200		
Lithium (ppm)	2.2		

Fig.1, 2 and 3 show the latest results of RUB and 3PB tests up to 32,600 hours of exposure with DH content of 25, 15 and 5ml STP/kgH₂O, respectively.

Each data plot shows the ratio of cracked specimens to the total at the exposure time at each inspection chance.

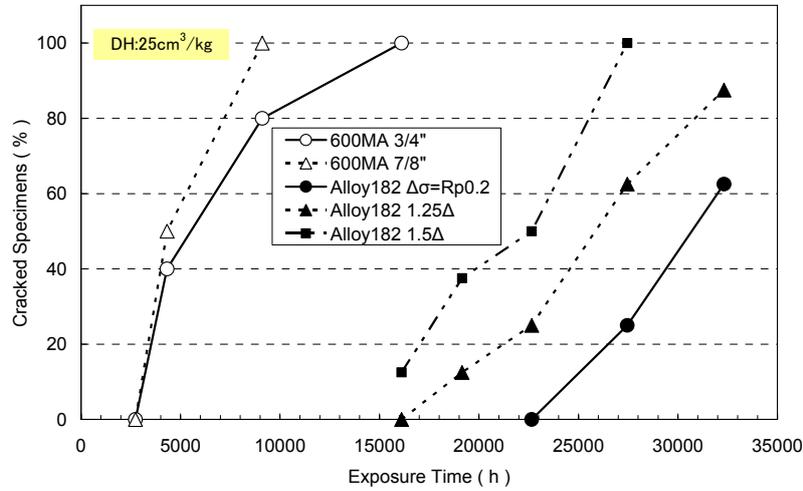


Fig.1 Change in Cracked Specimens Ratio with Exposure Time (Autoclave-1, 25ml STP/kgH₂O)

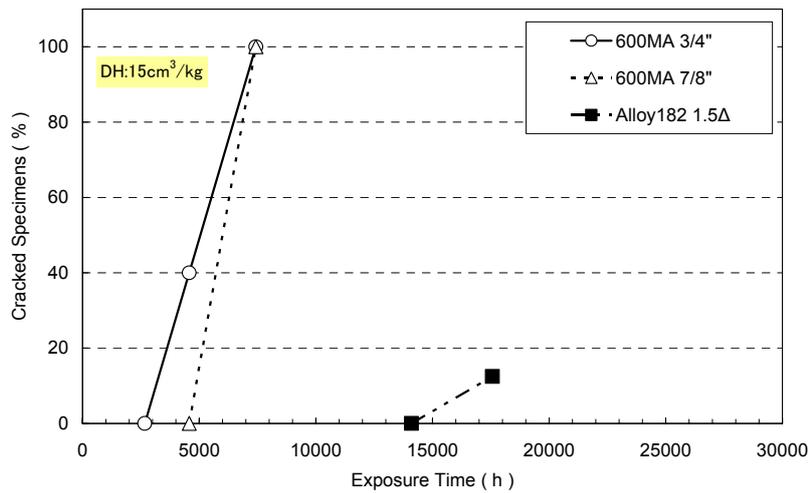


Fig.2 Change in Cracked Specimens Ratio with Exposure Time (Autoclave-2, 15ml STP/kgH₂O)

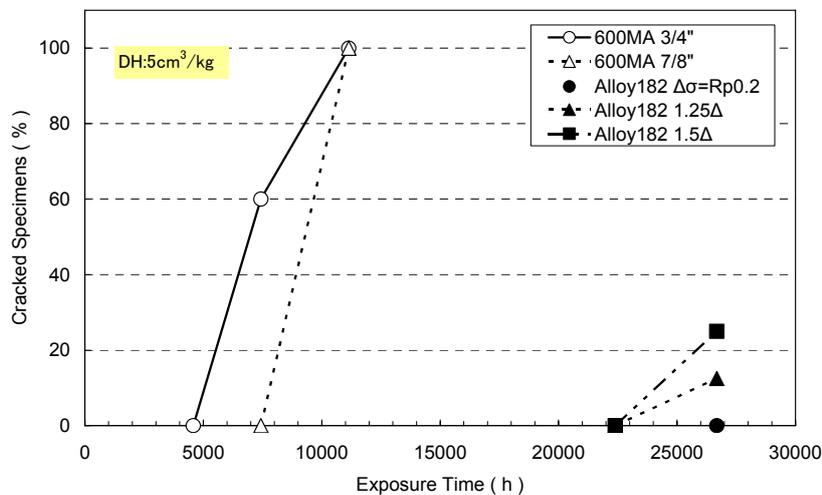


Fig.3 Change in Cracked Specimens Ratio with Exposure Time (Autoclave-3, 5ml STP/kgH₂O)

Fig.4 and Fig.5 show the data re-plot for each DH Content level of Alloy 600MA (Fig.4) and Alloy 182 (Fig.5). All specimens of Alloy 600MA have cracked but no specimens of Alloy 600TT have cracked at all. Note that some of the tests are still on-going for Alloy 182, though the clear difference of initiation property between 15~25 and 5 ml STP/kgH₂O is manifest.

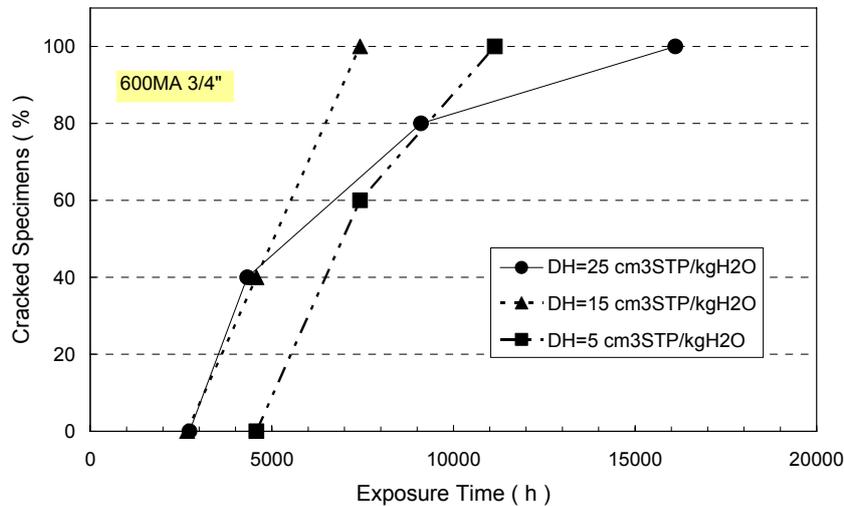


Fig.4 Change in Cracked Specimens Ratio for Each DH Content Level (Alloy 600MA)

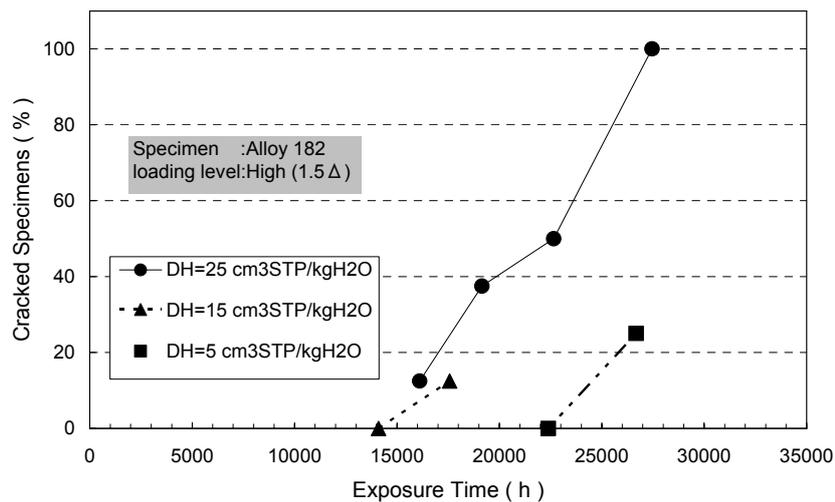


Fig.5 Change in Cracked Specimens Ratio for Each DH Content Level (Alloy 182)

Fig.6 shows a curve fitting result to have the dependency of DH content on the initiation property of Alloy 600 based on the data plots in Fig.4 using the tanh-function. Fig.7 gives the similar one for Alloy 182 based on Fig.5.

It is shown by Fig.6 that the difference between the environments with 25 and 15ml STP/kgH₂O is small, less than 10%, in time to crack initiation of Alloy 600MA. In the environment with the lowest hydrogen content, 5ml STP/kgH₂O, the initiation time for Alloy 600 MA is about 50% longer than in the other two environments.

In Fig.7, the curve for the environment with the highest hydrogen content (25ml STP/kgH₂O) has a good statistical basis (all eight specimens). For the other two environments (15 and 5ml STP/kgH₂O respectively) the curves are based on a few cracked specimens only. These few cracked specimens make it possible to estimate the position of the curve time-wise. The shape of the curve is assumed to be the same as for the curve related to the environment with the highest hydrogen level. For the environment with the lowest hydrogen content (5ml STP/kgH₂O), the difference in crack initiation time is about 50% compared to the other two environments, i.e. the same difference as for Alloy 600 MA.

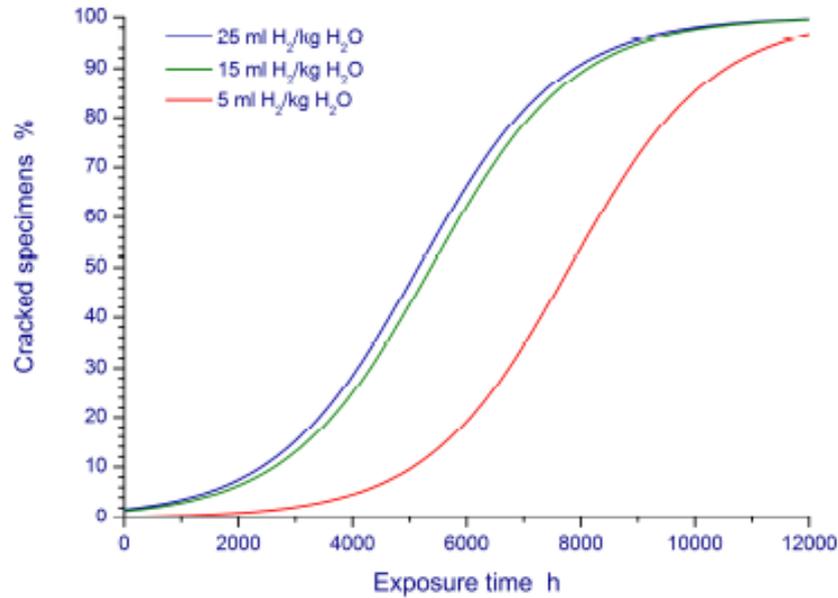


Fig.6 Dependency of DH Content on the Initiation Property of Alloy 600 [11]

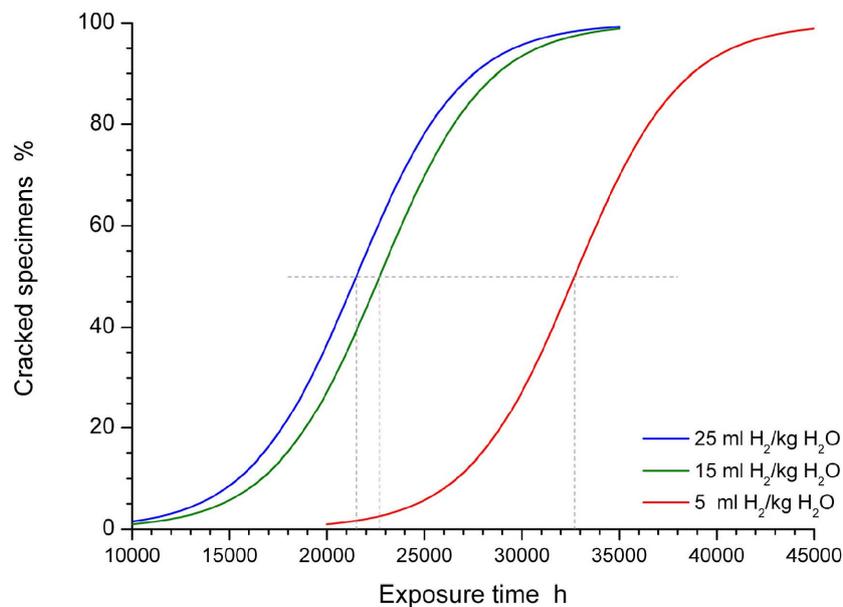


Fig.7 Dependency of DH Content on the Initiation Property of Alloy 182

2.2 Analyses of oxide and deposits

Selected specimens exposed within this project have been analyzed to try to clarify how hydrogen interacts with nickel-base alloys and influences the propensity to PWSCC. To get a better view of the surface appearance of different specimens, some were analyzed under FEG SEM (Field Emission Gun Scanning Electron Microscope). The main objectives of these analyses were:

- To demonstrate differences in oxides and deposits formed in the three environments with different hydrogen levels
- To demonstrate differences in oxide and deposits formed on Alloy 600 and Alloy 182

Typical appearances of the surface oxide, formed in environments with three levels of DH contents respectively, on Alloy 600 RUB-specimens and polished Alloy 182 3pb-specimens are shown in Fig.8.

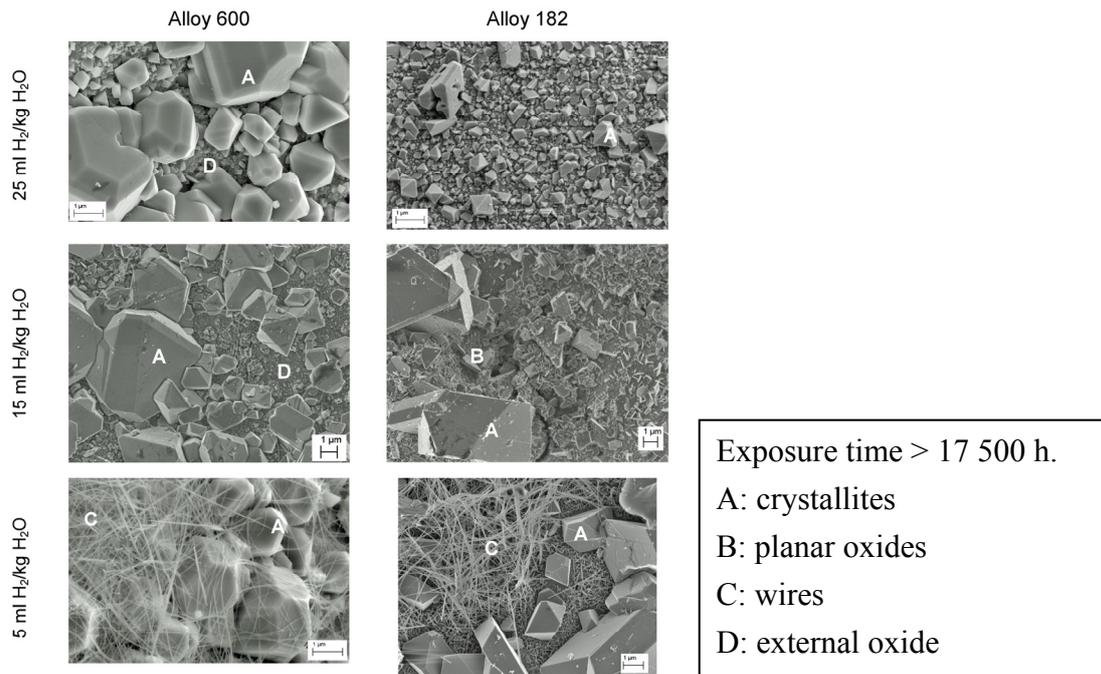


Fig.8 Typical surface oxides formed on Alloy 600 and Alloy 182 with three levels of DH content

A summary of the EDS analyses of the different types of oxides found on the surface of these specimens is shown in Fig.9.

- Crystallites – high Fe content. Probably of type $Ni_{(1-x)}Fe_{(2-y)}Cr_{(x+y)}O_4$.
- Planar oxide – bridging between crystallites and wire-like oxide
- Wire-like oxide – high Ni content
- External oxide – wide scatter

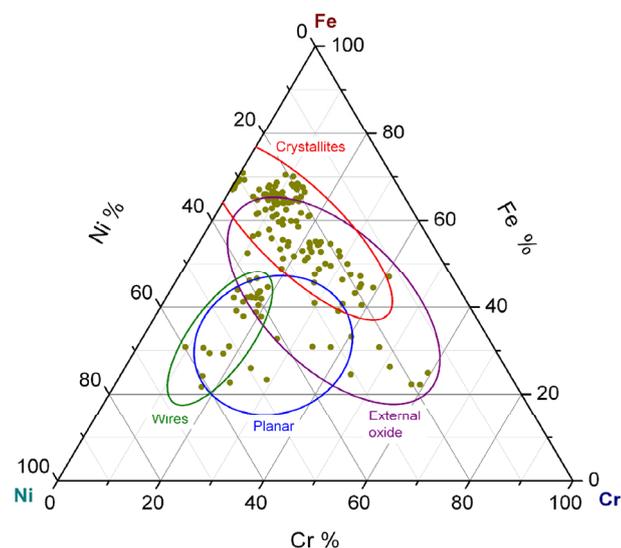


Fig.9 Summary of EDS-analyses of oxides formed on Alloy 600 and Alloy 182

With regard to the protectiveness of the inner chromium-rich oxide layer, not only the thickness but also the homogeneity and continuity are important issues. Fig.10 summarizes the differences with respect to all these properties of the oxides formed on Alloy 600 MA (8000~9000h of exposure), TT (18,000~22,000h of exposure) and polished weld metal 182 (22,500~30,000h of exposure) in the environments with 25 and 5ml STP/kgH₂O. The inner Cr-rich oxide layer formed on Alloy 600 in the environment with the lower hydrogen content is both homogeneous and continuous. The corresponding layer formed at the higher hydrogen level contains a number of Ni-ferrite crystals;

some of them bridging the entire inner oxide layer. At least for the MA material, the inner oxide layer appears not to be continuous in this case.

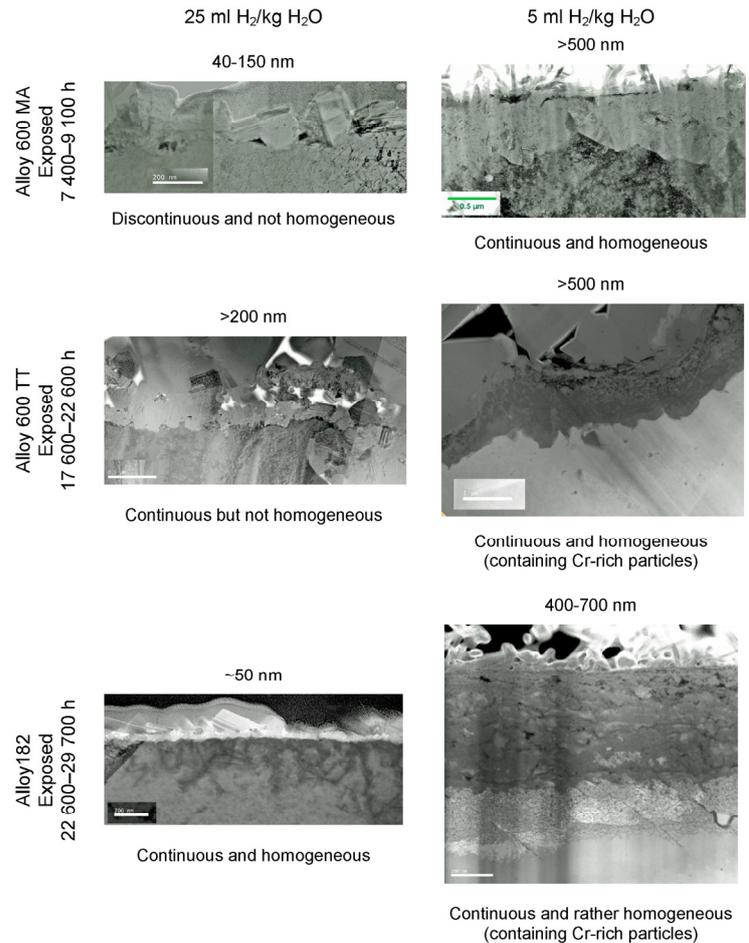


Fig.10 Average thickness and homogeneity of inner Cr-rich oxide layer

It should be mentioned that no pronounced nickel enriched or chromium depleted zone was observed beneath the metal/oxide interface in any of these Alloy 600 samples, Fig.11 and 12. It is possible that the nickel content was increased slightly. Oxygen was detected at grain boundaries without any visible oxide precipitation at least down to 1 μm beneath the metal/oxide interface. Fig.12 shows quantitative point analyses (EDS/TEM) through the base material and the inner oxide layer on Alloy 600 MA exposed for 7,400 hours in an environment with 5ml STP/kgH₂O.

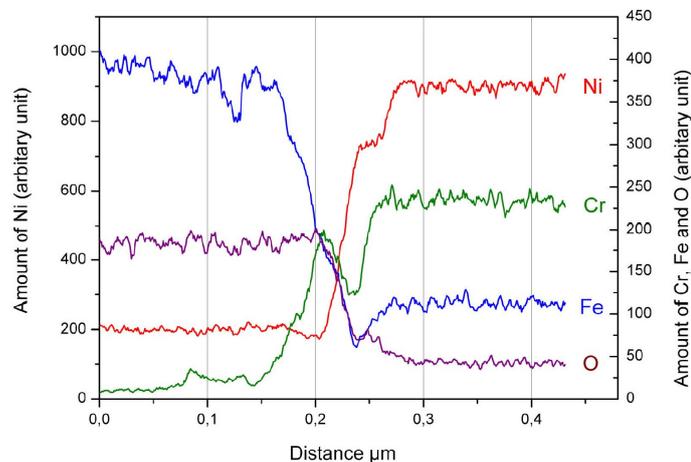


Fig.11 Line-Scan Analyses on Alloy 600 MA exposed for 7,400h with 25ml STP/kgH₂O DH Content

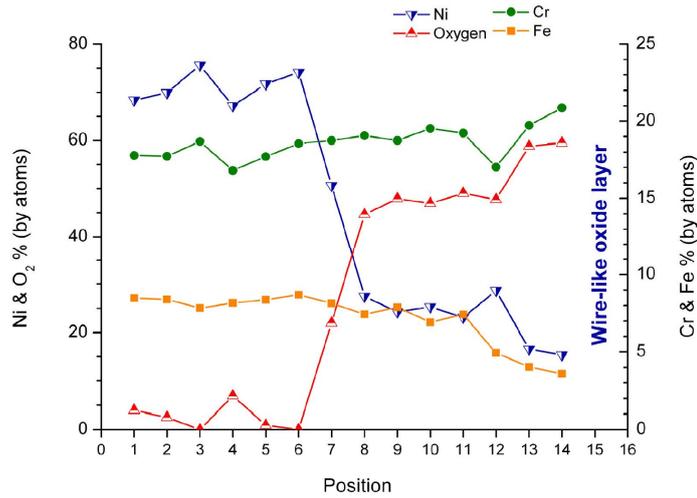


Fig.12 Quantitative Point Analyses (EDS/TEM) through Base Material and Inner Oxide Layer on Alloy 600 MA Exposed for 7,400h with 5ml STP/kgH₂O DH Content

EDS-line scans and point analyses are shown in Fig.13. The inner Cr-rich oxide layer has, in this case, very low Ni-content 16 (<5% Ni and 35~40% Cr). Grain or dendrite boundaries a few hundred nanometers below the metal-oxide interface show some enrichment in Ni and depletion in Cr.

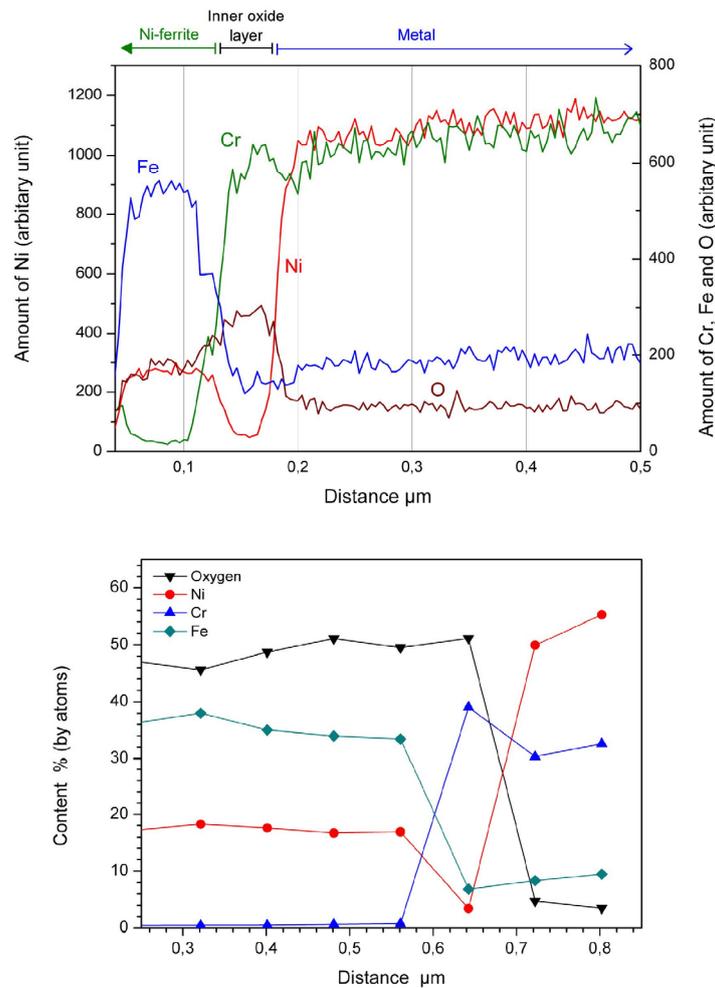


Fig.13 Line-Scan Analysis and Quantitative Point Analysis Made on Alloy 182 Exposed for 22,650h with 25 ml STP/kgH₂O DH Content

In recent years much attention has been paid to the Ni/NiO-line i.e. the oxidation of nickel. In the system illustrated in Figure 14 as a schematic summary of previous knowledge, the nickel containing oxides and mixed oxides with considerable Ni-content are found in the non-protective layers facing the aqueous environment. The only protective layer in this system is the inner chromium-rich oxide layer. The composition and thickness of this layer are dependent on such factors as the alloy composition and the aqueous environment. Connected to this layer is also the source of the chromium, which is the Cr-depleted layer just beneath the oxide/ metal interface. If the chromium oxide layer is discontinuous for some reason, the metal surface will be directly exposed to the aqueous environment. Thus, the protectiveness of the chromium oxide layer is of crucial importance to the influence of, among others, hydrogen on PWSCC. The importance of the chromium oxide layer is also supported by the fact that the Cr-content of the nickel-base alloy is known to be of vital importance for the PWSCC resistance.

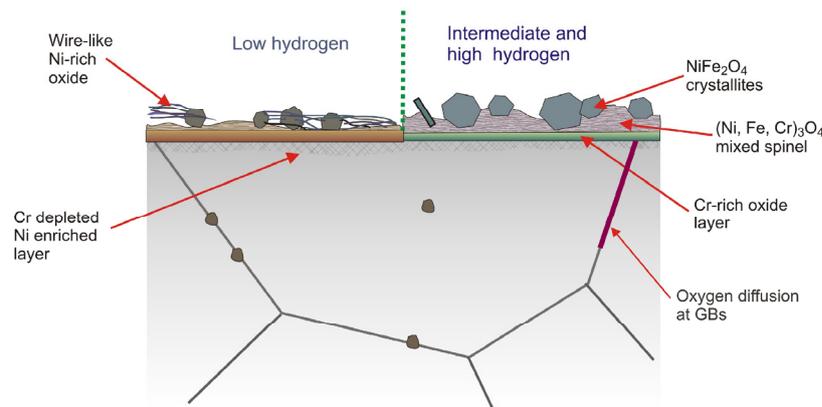


Fig.14 Outline of the interface region at lower (left) and intermediate to upper (right) DH levels

3. Current Status of Studies and Challenges for DH Optimization

3.1 PWSCC Initiation and Growth Property

Experimental data of the effect of DH on PWSCC initiation showed that lowering DH content has advantage to realize longer initiation time, but the test temperature was limited to around the hot leg temperature, 320°C or higher, because of the need for acceleration in laboratories. From the utilities' viewpoint, bottom mounted instrument (BMI) is the most important aspect in mitigating the environmental condition for PWSCC, because it is hard to repair or replace the penetrating part of BMI through the reactor vessel. The temperature of BMI in operation is about 290°C. Since it has not been clearly shown experimentally that PWSCC initiation is still DH content dependent at temperature as low as 290°C, the PWR Owners Group (PWROG) in Japan, Central Research Institute of Electric Power Industries (CRIEPI) and Mitsubishi Heavy Industries (MHI) are jointly conducting PWSCC initiation tests at 290°C.

Currently, the disposition lines of PWSCC CGR versus Stress Intensity Factor K for Alloy 600 and Alloy 182 are given in the Code Cases of the Japan Society of Mechanical Engineers (JSME) code for nuclear power generation facilities, Rules on Fitness-For-Service for nuclear power plants (JSME FFS Code). These disposition lines are based on the data obtained on the condition of environmental parameters of primary water currently controlled. Since some reports say that the PWSCC growth property has a convex upward dependency for DH content and the current control band of DH content is around the peak at hot leg temperature, it is expected to revise the disposition lines of PWSCCGR with new ones that are DH content dependent. Based on such new disposition lines, FFS Code rules can be improved so that utilities may gain advantages as far as flaw evaluation is concerned, and possibly inspection intervals as the benefit of introducing DH optimization as one of the environmental mitigation measures.

Flexibility and the feedback system in Code rules would be much more beneficial for the utilities, and for all stakeholders including regulatory bodies and the general public in the end than a fixed rule to have an incentive for improvement. Therefore, cumulative experimental data acquisition on DH content effect on PWSCC initiation and CGR is needed at industries, research institutes, universities and administrative bodies.

3.2 Other Possible Influences of DH Content Change

Possible influences, when DH content is changed, are given as follows,

- IASCC of stainless steel. Baffle former bolts (BFB) are managed to be inspected and replaced as necessary considering IASCC at below the bolt head. When DH content is changed, influence on IASCC behavior should be taken into account.
- IGSCC of cold-worked stainless steel. Work-hardened stainless steel by, for example, machining should be checked for its IGSCC property by changing DH content.
- IGSCC of stainless steel in contact with stagnant water. When DH is changed and the stainless steel is significantly irradiated, the reduction of oxidant content may be influenced and may change IGSCC properties.
- Integrity of fuel cladding material and fuel assembly material. When changing DH content, depending on the extent of the change, it is necessary to demonstrate the integrity of these materials. In-core tests using a test reactor is needed in such cases.
- Influence on the source of radiation dose. Since lower DH content may change the stable form of nickel, attaching behavior of nickel to fuel cladding may be changed and result in a change of source of radiation dose.

PWROG in Japan, CRIEPI and MHI are examining the previous studies and extracting the challenges left on those issues mentioned above.

4. Conclusion

Alloy 600 MA, Alloy 600 TT, and weld metal Alloy 182 specimens have been exposed for 2.5 to 4.5 years (17 500 to 32 600 h) in simulated primary PWR environments with 25, 15 and 5 ml STP/kg H₂O respectively. Inspections were performed to examine the ratio of cracked specimens to the total with suitable intervals. The following results were obtained.

- The difference in crack initiation time for Alloy 600MA RUB specimens in the two environments with the highest hydrogen levels, 25 and 15 ml STP/kg H₂O, is less than 10%. In the environment with the lowest hydrogen content, 5 ml STP/kg H₂O, the PWSCC initiation time is about 50% longer than in the other two environments.
- The behavior of Alloy 182 indicates that, as with Alloy 600 MA, the difference caused by a reduction of hydrogen from 25 to 15 ml STP/kg H₂O is small. For the environment with the lowest hydrogen content (5 ml STP/kg H₂O), the crack initiation time is about 50% longer than in the other two environments, i.e. the same difference as for Alloy 600 MA. Thus, the effect of hydrogen on the initiation of PWSCC is the same for Alloy 600MA and weld metal Alloy 182.
- No cracks have been detected in the Alloy 600 TT RUB specimens.
- The oxides visible on the surface of the specimens are made up of multilayered structure.
- The inner, chromium-rich oxide layer formed on Alloy 600 and Alloy 182 at 5ml STP/kgH₂O is thicker than the corresponding oxide formed at 25ml STP/kgH₂O.
- The inner chromium-rich oxide layer formed on Alloy 600 at 5ml STP/kgH₂O is both homogeneous and continuous, while the corresponding layer formed at 25ml STP/kgH₂O contains a number of nickel-ferrite crystals, some of them bridging the entire inner oxide layer. This difference seems to be of great importance when considering the PWSCC susceptibility.

Current status of studies and challenges for DH optimization were summarized. Further investigation on this issue is encouraged not only for industries but also for research laboratories and administrative bodies.

References

- [1] E. J. Hart, W. R. McDonell, and S. Gordon, The Decomposition of Light and Heavy Water Boric Acid Solutions by Nuclear Reactor Radiations, Proc. of IAEA Conference in Geneva, Vol. 7, p593, Switzerland 1955
- [2] H. Takiguchi, M. Sekiguchi, H. Christensen, J. Flygare, A. Molander, and M. Ullberg, In-Pile Loop Experiment and Model Calculations for Radiolysis of PWR Primary Coolant, Proc. of BNES 8th Int. Conf. On Water Chemistry of Nuclear Reactor Systems 8, Bournemouth, UK, 2000
- [3] N. Nagata, H. Ichige, K. Dozaki, and H. Takiguchi, Study on Optimum Concentration Band of Dissolved Hydrogen in PWR Primary System – In-Core Measurement of Electrochemical Corrosion Potential in Tsuruga-2, Fontevraud 6, Fontevraud, France, Vol.1, p.335, Sep. 2006
- [4] N. Totsuka S. Sakai, M. Kamaya, N. Nakajima, and H. Mitsuda, A New Evaluation Method for Short Crack Growth and Influence of Dissolved Hydrogen on PWSCC of Alloy 600, Proc. of 10th International Symposium on Environmental Degradation of Materials in Nuclear Power Systems -Water Reactors-, Lake Tahoe, 2001
- [5] P. Andresen, International Workshop on Optimization of Dissolved Hydrogen Content in PWR Primary Coolant, Sendai, 2007
- [6] P.L. Andresen, J. Hickling, A. Ahluwalia, and J. Wilson, Effects of Hydrogen on Stress Corrosion Crack Growth Rate of Nickel Alloys in High-Temperature Water, Corrosion vol.64 No.9, Sep. 2008
- [7] D.S. Morton, S. A. Attanasio, E. Richey, and G. A. Young, In Search of the True Temperature and Stress Intensity Factor Dependencies for PWSCC, Proc. of 12th International Symposium on Environmental Degradation of Materials in Nuclear Power Systems -Water Reactors-, Salt Lake City, 2005
- [8] T. Tsuruta, Proc. of Spring Technical Meeting, Japan Society of Corrosion Engineering, p78, 1983
- [9] A. Molander, International Workshop on Optimization of Dissolved Hydrogen Content in PWR Primary Coolant, Sendai, 2007
- [10] C. Soustelle, M. Foucault, A. Gelpi, P. Combrade, and T. Magnin, PWSCC OF Alloy 600:A Parametric Study, Proc. of EUROCORR'98, the Netherlands, 1998
- [11] D. Akutagawa, N. Nagata, K. Dozaki, H. Takiguchi, K. Norring, A. Jenssen, and A. Molander, Environmental Mitigation OF PWSCC Initiation - LOW DH Chemistry FOR PWR Primary System, Proc. of 14th International Symposium on Environmental Degradation of Materials in Nuclear Power Systems -Water Reactors-, Virginia Beach, 2009