Environmental Mitigation for SCC Initiation of BWR Core Internals by Hydrogen Injection during Start-up

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1. Background

In Japan, we have experienced not a few cases of Stress Corrosion Cracking (SCC) not only in BWR power stations but also in PWR since 1990's (Fig.1).

To take preventive measures for SCC, it would be the best way to combine mechanical and environmental measures well considering effectiveness of each countermeasure, impact on economy, side effect, and so on (Table-1). Especially, our focus is on the influence of dynamic stress (strain) produced during the plant start-up on the initiation of SCC (Fig.2).

2. Concept of Hydrogen Water Chemistry During Start-up

Hydrogen injection into the reactor water has been applied to many BWR power stations. Since hydrogen injected accelerates recombination of oxidant generated by water radiolysis, oxidant concentration, such as dissolved oxygen concentration in reactor water can be reduced. As the result of the reduction of oxidant concentration, Electrochemical Corrosion Potential (ECP) at the surface of structural material can be lowered. Lowered ECP moderates Stress Corrosion Cracking (SCC) sensitivity of structural materials, such as stainless steels.

As usual, hydrogen injection system begins to work after the plant start-up is finished, when the condition of normal operation is established. Accordingly, Hydrogen Water Chemistry (HWC) does not cover all the period of plant operation. As far as SCC crack growth is considered, loss of HWC during plant start-up does not result in significant crack growth, because the duration of plant start-up is much shorter than that of plant normal operation, when HWC condition is being satisfied.

However, the reactor water environment and load conditions during a plant start-up may contribute to the initiation of SCC (Fig.3, Fig.4). It is estimated that the core internals are subjected to the strain rate that may cause susceptibility to SCC initiation during start-up (Fig.5). Dissolved oxygen (DO) and hydrogen peroxide (H_2O_2) has a peak, and ECP is in high levels during start-up (Fig.6, Fig.7). Therefore it is beneficial to perform hydrogen injection during start-up as well in order to suppress SCC initiation.※ We call it <u>H</u>WC <u>D</u>uring <u>S</u>tart-up (HDS) here.

Although it takes a few days to finish the whole operation of plant start-up, it is not necessary to perform hydrogen injection during the whole period of start-up. It will be adequate to perform hydrogen injection only during rising period of pressure and temperature, because load and environmental conditions are much severer than during the subsequent period (Table-2).

Since HDS is applied during the very early stage of the plant operating cycle, the injected hydrogen volume necessary to suppress the oxidant concentration is much smaller than the amount injected during normal plant operation. In the case of Tokai-2, the total hydrogen injection volume needed for HDS is approximately equivalent to the amount consumed in three hours by conventional HWC during normal operation. The hydrogen volume is small enough so that the injection equipment can be designed as a simple, small-scale system. Therefore, HDS introduction does not represent a significant cost in terms of initial investment or operation (Fig.8).

3. Expect for HDS

A series of cyclic, slow strain rate tensile (SSRT) tests were carried out to evaluate the influence of water chemistry on SCC initiation characteristics of sensitized Type 304 stainless steel. The temperature and stress conditions occurring in the "heat-up" period during start-up were simulated for the test. Six runs under NWC conditions and four runs under HWC conditions were performed (Fig.9, Fig.10).

All four specimens exposed to HWC conditions did not fail even after 40 cycles, while all six specimens exposed to NWC conditions fractured within three cycles. The correlation between time-to-failure and cumulative probability of failure is plotted (Fig.11). Based on statistical analysis of test results, the minimum time-to-failure for NWC conditions is 28 hours. The corresponding value for HWC conditions is 1032 hours and suggests that improved start-up water chemistry could extend the time-to-failure of sensitized Type 304 stainless steel by at least 36 times.

From the test results, it is pointed out that stress and water chemistry during the rising period of pressure and temperature produce possibility of SCC initiation. Therefore, it is expected to be useful to improve water chemistry during this period for preventing SCC initiation

4. Effect of HDS

In December 2002, a trial HDS was performed at Tokai-2 Power Station (1100MWe BWR, started commercial operation in 1978) after 19th refueling and maintenance outage. An additional hydrogen injection system was installed for this purpose.

As the results of this trial HDS, environmental improvement was clearly observed. Peak values of Dissolved Oxygen (DO) and hydrogen peroxide (H_2O_2) concentrations on the order of several hundred ppb were achieved under NWC conditions. These peaks were suppressed and in fact decreased below a detectable level with the continuous injection of hydrogen (HDS) (Fig.12).

Decreased ECP after 100°C, being measured at reactor bottom drain, had been reached due to HDS and remained below -200 mV vs. SHE.

The target potential (below equivalent of -230 mV vs. SHE by transformation to 280°C) was satisfied due to hydrogen injection in the start-up regions above 150°C (Fig.13).

DO concentration history was drawn with increasing temperature during this start-up with HWC and during the previous start-up with NWC (Fig.14). The shaded region in this figure was proposed as the region of SCC susceptibility in reference [2]. As can be seen, the NWC DO history intersects with the limit line, indicating that SCC initiation may occur during start-up under NWC conditions. In contrast, the DO history under HWC conditions is shifted downward and escapes this "high risk zone".

5. Summary and future plan

It was confirmed that HDS application clearly improved the reactor water environment with respect to SCC susceptibility. DO and H_2O_2 concentration peaks are eliminated. ECP was maintained below the target value corresponding to -230 mV vs. SHE at 280°C, except during the very initial stage when temperatures are lower.

In the future, hydrogen injection scheme will be optimized. HDS operation will be regularized from trial to a routine. Study on expansion of hydrogen injection to shutdown will be investigated.

References

[1] Abe, Tobita, Nagata, Dozaki and Takiguchi, "Mitigation of SCC initiation on BWR core internals by means of hydrogen water chemistry during start-up," Nuclear Science and Engineering, ANS, to be published in March 2005.

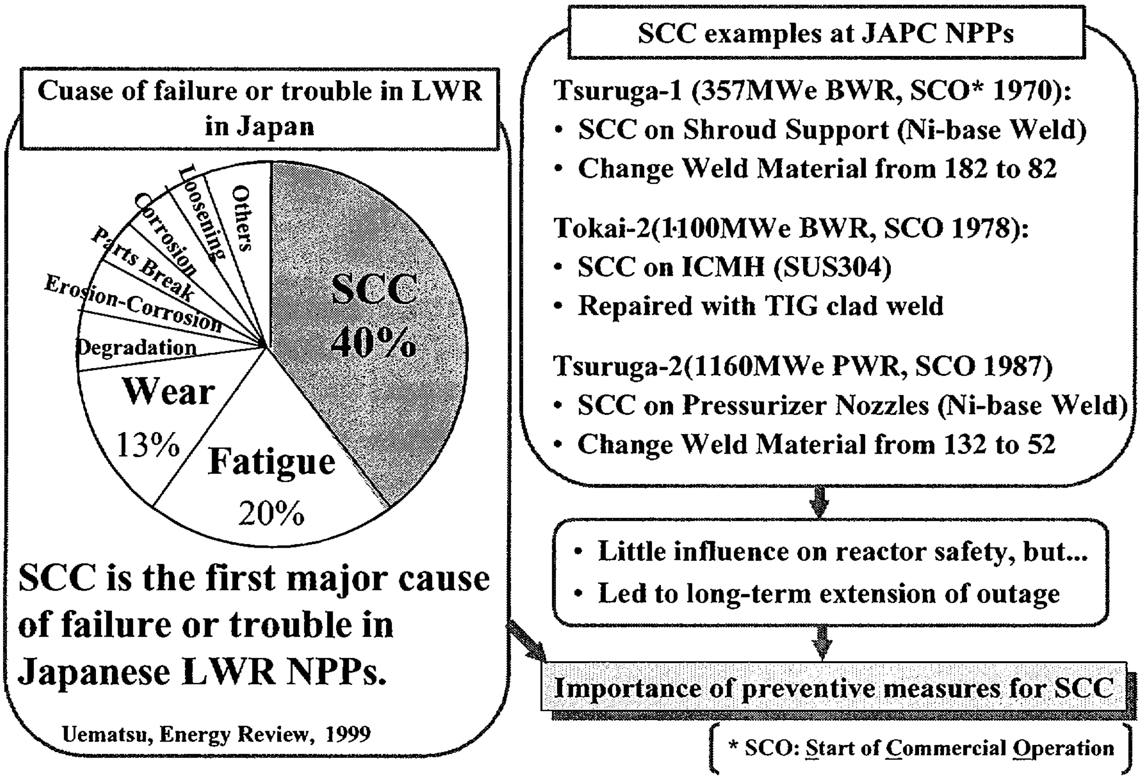
[2] F.P. Ford, "The Effect of Oxygen Temperature Combinations on the Stress Corrosion Susceptibility of Sensitized Type 304 Stainless Steel in High Purity Water," National Association of Corrosion Engineering, Vol. 35, No. 12, pp 569-574, December 1979.

Table-1 Features of Preventive Measures for SCC

	Environmental Improvement	Mechanical Improvement
Effective Areas	Wide (Around the loop)	Narrow Limited to the portion taken care of
Impact on Outage Period	Less	More
Cost Effectiveness	More	Less
Side Effect	Yes (Necessary to consider)	No

Table-2 Difficulties of Hydrogen Injection During Whole Period of Start-up

	Whole Start-up Period (3-4days)	Normal operation
Equipment	Frequent operation is needed	Few operation (fixed condition)
Pressure	Direct injection into reactor (High pressure: 7MPa)	Injection into feedwater (Low pressure: <1MPa)
Volume control	Necessary volume changes in wide range (0-36Nm^3/hr) Automatic control is not applicable	60-100% of full power (22-36Nm^3/hr) Control proportional to feedwater flow



SCC is the first major cause of failure or trouble in Japanese LWR NPPs.

Uematsu, Energy Review, 1999

SCC examples at JAPC NPPs

Tsuruga-1 (357MWe BWR, SCO* 1970):
- SCC on Shroud Support (Ni-base Weld)
- Change Weld Material from 182 to 82

Tokai-2(1100MWe BWR, SCO 1978):
- SCC on ICMH (SUS304)
- Repaired with TIG clad weld

Tsuruga-2(1160MWe PWR, SCO 1987)
- SCC on Pressurizer Nozzles (Ni-base Weld)
- Change Weld Material from 132 to 52

- Little influence on reactor safety, but...
- Led to long-term extension of outage

Importance of preventive measures for SCC

* SCO: Start of Commercial Operation

Fig.1 Importance of preventive measures for SCC

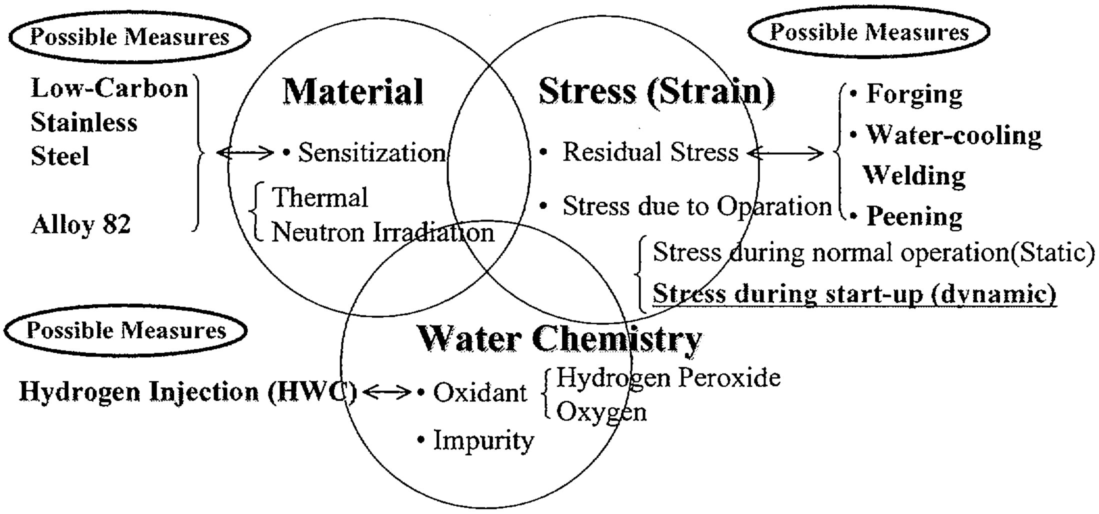


Fig.2 Effectiveness of Multiple Countermeasure and Importance of Plant Start-up

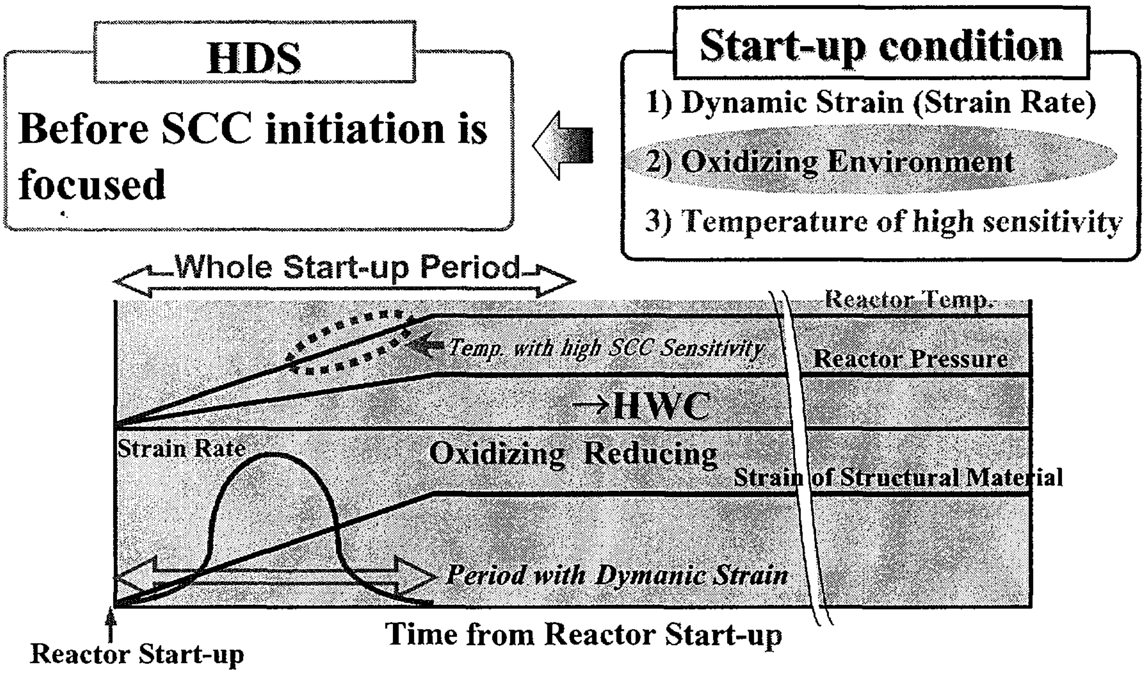
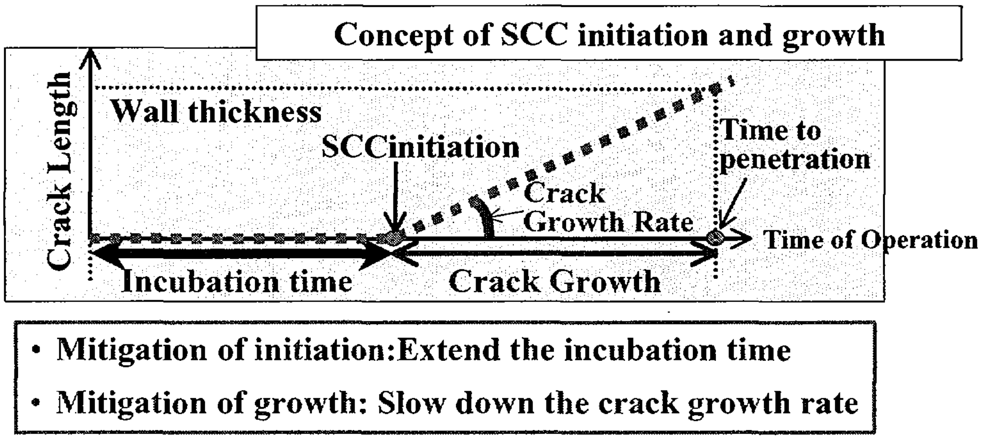
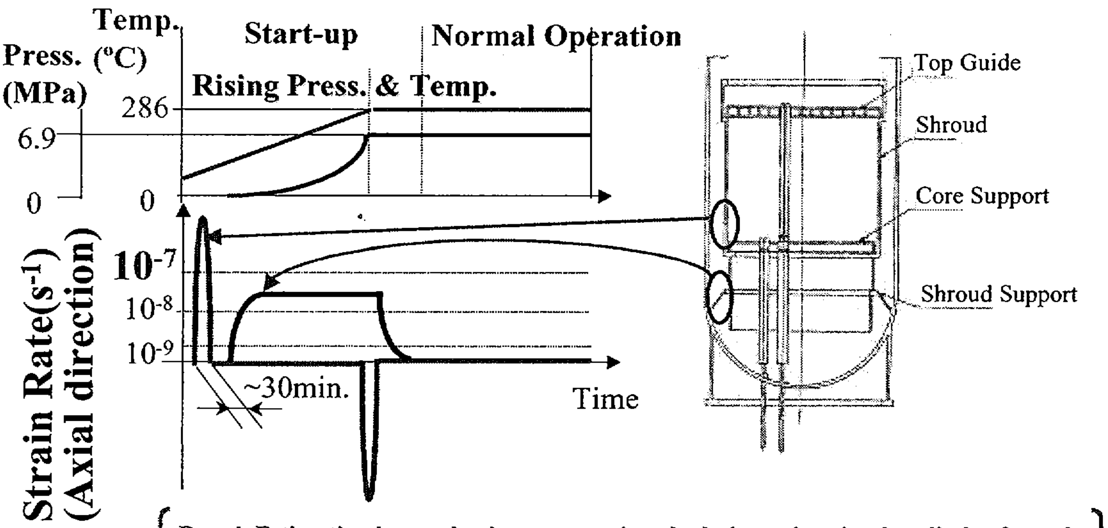


Fig.3 Features of HWC During Start-up (HDS)



- Mitigation of initiation:Extend the incubation time
- Mitigation of growth: Slow down the crack growth rate

Fig.4 Relationship between SCC Initiation, Growth and HWC



[Rough Estimation by an elastic stress-strain calculation using simple cylinder formula]

Fig.5 Stress (Strain Rate) evaluation during start-up

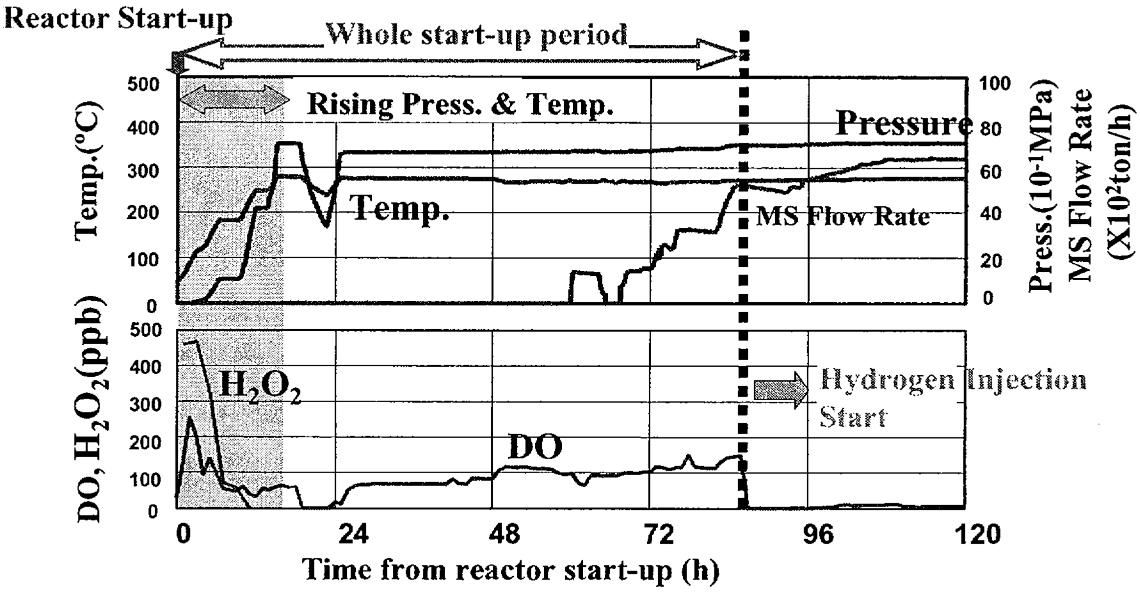


Fig.6 Water chemistry evaluation during start-up

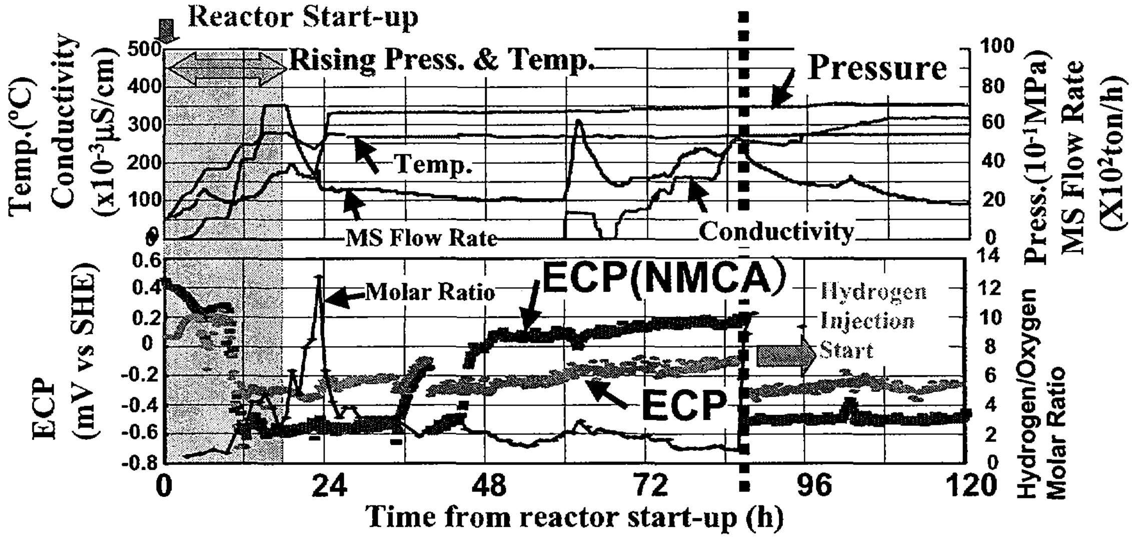
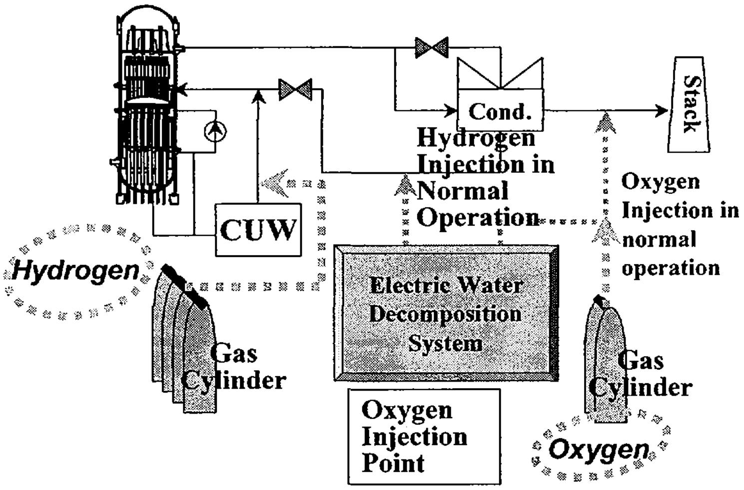


Fig.7 Electrochemical Corrosion Potential (ECP) evaluation during start-up

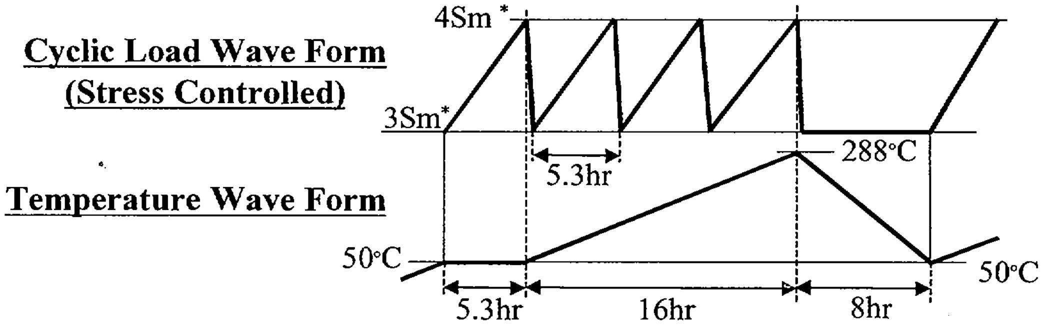


Partly Modified Exsting Oxygen Injection System

HDS	HWC in Normal Operation
• Manual and in-situ operation • Injection rate: 100m^3/20hr (5m^3/hr) • Gas Cylinder (Bombe) • Installation cost is about 1/20 of the existing one	• Automatic and remote operation • Injection rate: 36m^3/hr • Electric Water Decomposition System

Fig.8 Hydrogen Injection Method in HDS

O Load & Temp. condition



*) Sm: Stress intensity for design defined by ASME Boiler & Pressure Vessel Code Sec.III

O Strain rate

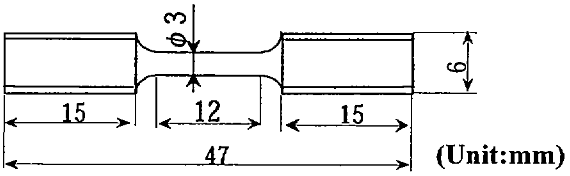
Stress ramp change from 3Sm to 4Sm during 5.0hr leads to tensile strain rate approximately 4x10^{-7} (1/s).

Fig.9 Load and Temperature Condition for Cyclic SSRT Tests

O Specimen

Sensitized SUS304 SS

O Shape of Specimen



O Chemical Composition

Element	C	Si	Mn	P	S	Cr	Ni	Fe
%	0.07	0.44	0.87	0.028	0.001	18.16	8.22	Bal.

O Heat Treatment:

620°C×24hr

Fig.10 Description of Test Specimen for Cyclic SSRT Tests

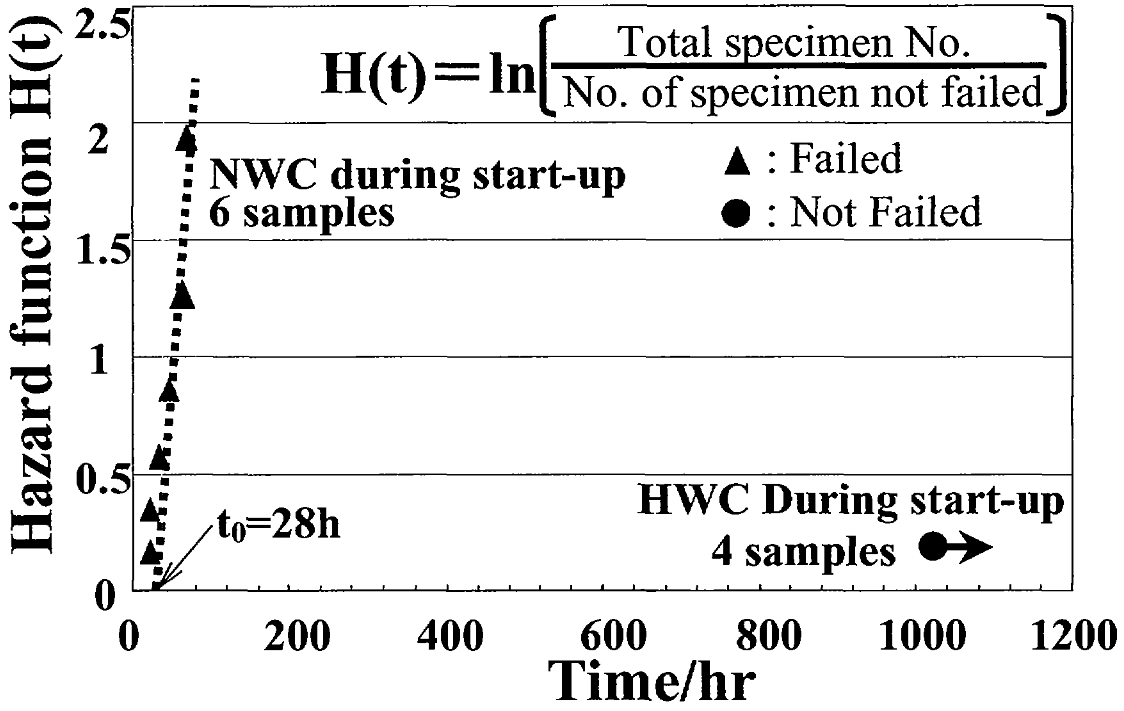


Fig.11 Cyclic SSRT Test results

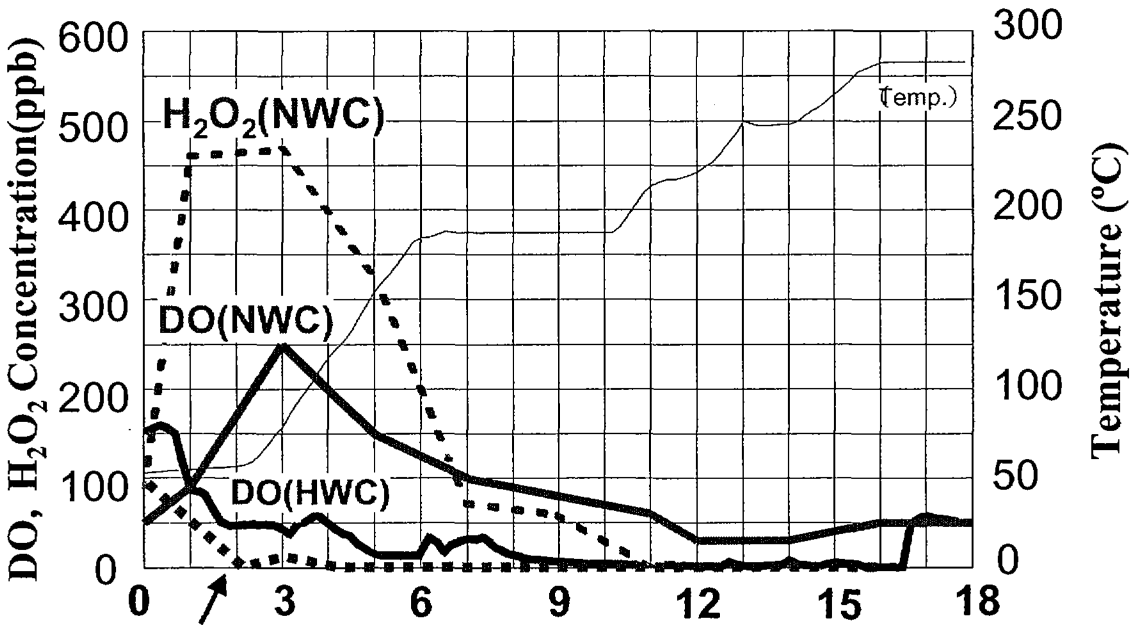


Fig.12 Reduction of oxidant concentration due to HDS

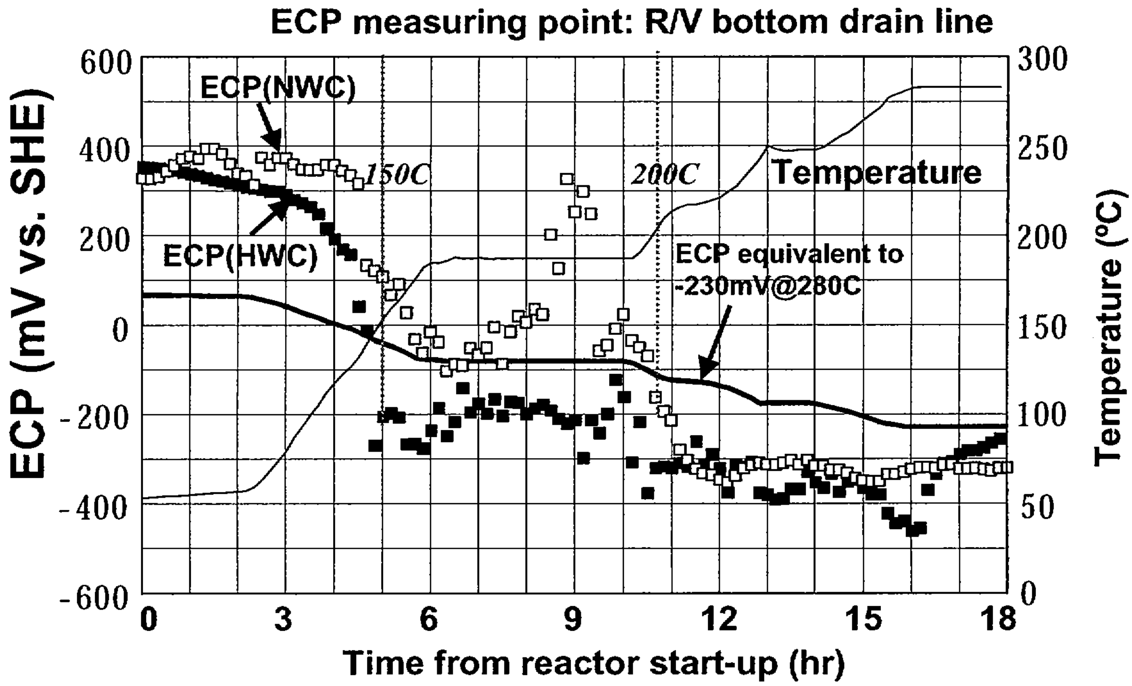
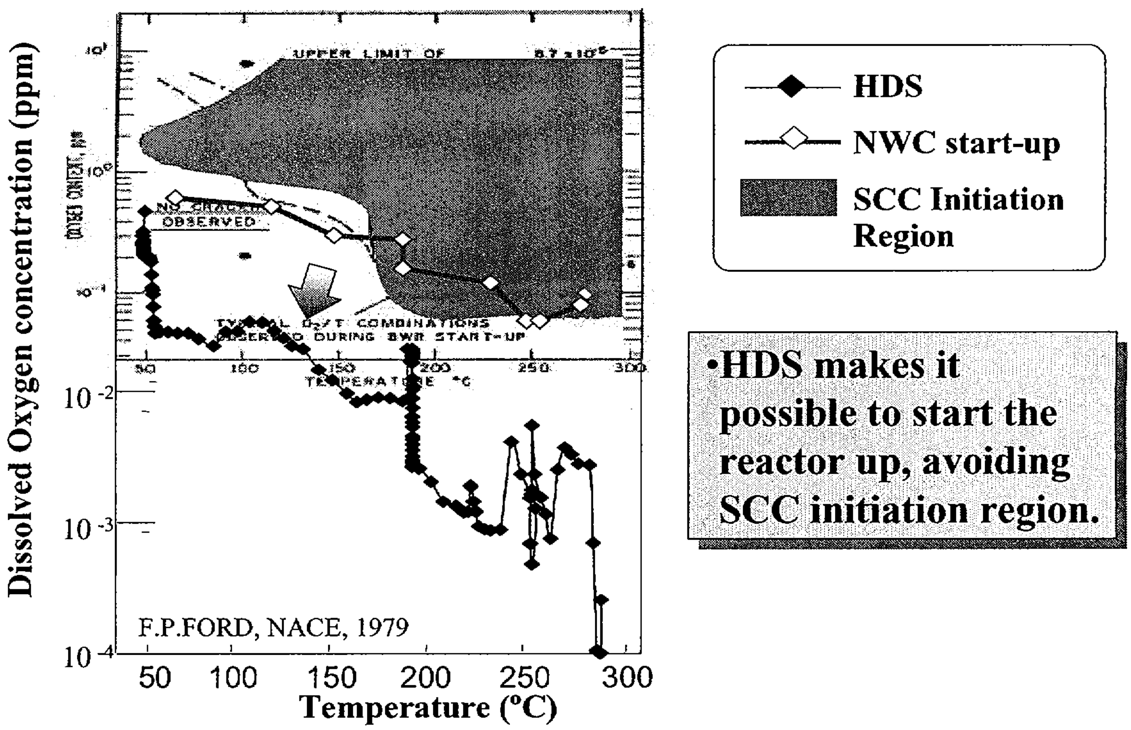


Fig.13 ECP Decrease due to HDS



•HDS makes it possible to start the reactor up, avoiding SCC initiation region.

Fig.14 Avoidance of SCC initiation sensitivity