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Study on PWSCC Susceptibility Index Considering Threshold Value

HyungJun Kim*, JuneHo Chung, TaeRyong Kim
KINGS, 1456-1, Shinam-ri, Seosaeng-myeon, Ulju-gun, Ulsan, 689-882
**Corresponding author: junasen@hanmail.net*

1. Introduction

Primary Water Stress Corrosion Cracking (PWSCC) of alloy 600 base metal is unique aging mechanism that is occurring in primary water environment in nuclear power plant. To manage PWSCC phenomenon, priority ranking is designated by using PWSCC susceptibility index. Westinghouse model is well used method in PWSCC susceptibility index calculation and the past Alloy 600 aging management program is also made by using PWSCC susceptibility index in Korea.

In this paper, Westinghouse model was reviewed and the improvement of PWSCC susceptibility index considering threshold value is discussed.

2. PWSCC Susceptibility Index

In this section, three PWSCC susceptibility factors and Westinghouse model will be introduced which is used for KORI unit 1 PWSCC susceptibility analysis. And also, it will be reviewed and verified as a PWSCC susceptibility quantification model.

2.1 Three PWSCC Susceptibility factors

PWSCC of Alloy 600 in PWR plants can be occurred, when three conditions are met together, like susceptible material (Alloy 600) and stress (tensile stress) and corrosion circumstances (susceptible temperature) [1].

The susceptibility of a specific component or weld to PWSCC is dependent on multiple factors such as:

- Material factors
  (material properties, metallurgical characteristics, material processing history, welding method & process, repair history)
- Temperature factors
  (time-temperature history)
- Applied stresses
  (fabrication residual stress, operation stress, operational environment, industry and plant experience with a particular component type)

2.2 Definition of Westinghouse Model

Westinghouse model has the quantitative susceptibility index which can evaluate diverse component and weld zone's susceptibility individually. It has three factors like material index, stress index, temperature index.

F_m, material index has a value of from 0 to 1, as a microstructure material index [2].

< F_m Determination Method >

Material	Shape	Thermal history	F_m
Alloy 600	Plate	Hot worked	0.3
	Pipe	Annealed	0.5
	Pipe	Annealed, Worked	0.4
	Heavy-walled	Hot worked	0.5
	Forged	Hot worked	0.25
Alloy 82	Weld meal	As-welded	0.1
Alloy 182	Weld mtal	As-welded	0.15

F_s, as an effective stress index can be drawn by below equation. And residual stress factor, k can be determined by below Table [2].

$$F_s = (\sigma_a + k\sigma_y)^4 \quad (\text{if, k<1})$$
$$\quad = (k\sigma_y)^4 \quad (\text{if, k}\geq 1)$$

Here, F_s is a stress factor
k is residual stress factor
σ_y is the yield stress (ksi)
σ_a is the applied stress (ksi)

< k Determination Method >

Region	Fabrication Process	k
Base metal / Heat Affected Zone (HAZ)	Annealed condition	0
	As-manufactured (Hot / Cold working)	$1+\frac{7ksi}{\sigma_y}$
	Base metal nearby weld zone	0.5
Weld metal	As-welded (Not Post Weld Heat Treatment)	0.95
	Post Weld Heat Treatment	0.5
	Welding or Surface cold working after final manufacturing	1.2
	many welding cycle (include repair welding)	1.25

F_t, as a temperature index can be drawn by below equation [2].

$$F_t = \exp\left(-\frac{Q}{RT}\right)$$

Here, F_s is a temperature factor
Q is the apparent activation energy (209430 J/mole)
R is the universal gas constant (8.134 J/mole/K)
T is the absolute temperature (K)

Finally, synthesizing the above three factors, we can get total susceptibility index (SI) which means inverse number of PWSCC initiation time using below equation [2].

$$\text{Susceptibility Index(SI)} = F_m \times F_s \times F_t$$

Here, F_m is a material factor
F_s is a stress factor
F_t is a temperature factor

2.3 Review of Westinghouse Model

Using the above quantitative processes, each factor and total susceptibility index were calculated for KORI unit 1 as shown in below Table. Based on the calculated total susceptibility index, Alloy 600 components were ranked to prioritize the expenditure of resources for mitigation, replacement, and additional inspection beyond requirements for Alloy 600 aging management program.

< KORI-1 Westinghouse Susceptibility Analysis Result >

Component	Part and Location	k	F_m	F_T	F_S	SI	Ranking
	Base Metal						
Reactor Pressure Vessel	CRDM Penetration Nozzle	1.62	0.5	2.0337E-19	2.1918×10^7	2.2287E-12	2
	Vent Line Nozzle	1.3	0.4	2.0337E-19	1.4909×10^7	1.2128E-12	3
	BMI Penetration Nozzle	1.3	0.5	2.2575E-20	1.5161×10^7	1.7113E-13	8
	Safety Injection Nozzle	0.5	0.25	3.0972E-19	9.1166×10^5	7.0590E-14	9
	Core Support Pads	0.5	0.25	2.2575E-20	1.3170×10^5	7.4326E-18	13
	Weld Metal						
	CRDM Penetration Nozzle	1.3	0.15	2.0337E-19	3.0361×10^7	9.2616E-13	4
	Vent Line Nozzle	0.95	0.15	2.0337E-19	1.2886×10^8	3.9310E-12	1
	BMI Penetration Nozzle	0.95	0.15	2.2575E-20	1.3455×10^7	4.5561E-14	10
	Cold Leg Nozzle	0.95	0.15	2.2575E-20	1.3173×10^7	4.4606E-14	11
	HotLeg Nozzle	0.95	0.15	3.0972E-19	1.2320×10^7	5.7235E-13	6
	Safety Injection Nozzle	0.95	0.15	3.0972E-19	1.8121×10^7	8.4187E-13	5
	Core Support Pads	0.95	0.15	2.2575E-20	1.1572×10^7	3.9186E-14	12
	Leak-off Monitor Holes	0.95	0.1	3.0972E-19	1.0187×10^7	3.1551E-13	7

As seen in the Table, Westinghouse model seems to be very effective and convenient susceptibility analysis method.

But, the value of temperature factor (F_t) is relatively too small comparing with other indices. It means that temperature factor does not have any effects on the total susceptibility index in Westinghouse model. This is contradictory to the general theory that the temperature is the most affective factor to PWSCC. And in case of stress factor (F_s), it does not consider value of threshold stress at all and the value is too big. Therefore, we need some modifications to make the factors have reasonable values by using reference value or threshold value.

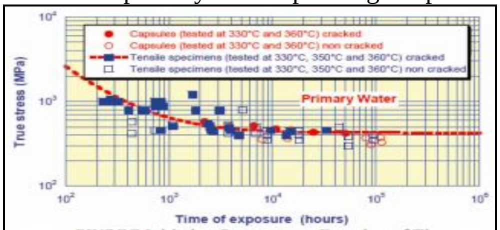
3. Normalization of Susceptibility Index by Threshold Value

For non-dimensionalization of PWSCC susceptibility index, the normalization of temperature factor and stress factor against reference value and threshold value is attempted in this paper.

3.1 Normalization of stress index

Threshold value means the point that must be exceeded to begin producing a given effect or result or to elicit a response. So, when we judge crack initiation of Alloy 600 components, threshold stress value can be clear and appropriate criteria.

Below figure is PWSCC initiation stresses vs. time of exposure [2]. According to the graph, threshold stress of alloy for PWSCC initiation is about 450 MPa (= 65.27 ksi) at the usual primary water operating temperature.



PWSCC Initiation Stresses as a Function of Time

It is reasonable to use this threshold value for the normalization of stress factor in Westinghouse model as follows;

$$F_s = \left(\frac{\sigma_a + k\sigma_y}{65.27}\right)^4 \quad \text{(if, k<1)} \qquad \text{Here, 65.27 is threshold stress (ksi)}$$
$$= \left(\frac{k\sigma_y}{65.27}\right)^4 \quad \text{(if, k}\geq\text{1)}$$

3.2 Normalization of temperature index

As mentioned earlier, the value of temperature factor in Westinghouse model is evaluated very insignificant value in total susceptibility index. This imbalance of susceptibility index value is resulted from non-normalization of temperature data.

The normalization means that adjusting the expression of value to indicate in a fixed range in advance. So we need reference temperature value to normalize temperature index. The temperature of 325°C (598°K) can be a reference temperature, which is average temperature of primary water in nuclear power plant.

$$F_t = exp\left[\left(\frac{-Q}{R}\right)\left(\frac{1}{T} - \frac{1}{598}\right)\right] \qquad \text{Here, 598 is the reference temperature (K)}$$

3.3 Result of normalized Westinghouse Model

< KORI-1 corrected Westinghouse Susceptibility Analysis Result >

Component	Part and Location	k	F_m	F_T	F_S	SI	Ranking
	Base Metal						
Reactor Pressure Vessel	CRDM Penetration Nozzle	1.62	0.5	4.0298E-01	1.2133	2.4448E-01	2
	Vent Line Nozzle	1.3	0.4	4.0298E-01	8.2147E-01	1.3241E-01	3
	BMI Penetration Nozzle	1.3	0.5	4.4763E-02	8.3537E-01	1.8697E-02	8
	Safety Injection Nozzle	0.5	0.25	6.1378E-01	5.0231E-02	7.7078E-05	10
	Core Support Pads	0.5	0.25	4.4763E-02	2.0934E-01	2.3427E-05	13
	Weld Metal						
	CRDM Penetration Nozzle	1.3	0.15	4.0298E-01	1.6728	1.0112E-01	4
	Vent Line Nozzle	0.95	0.15	4.0298E-01	7.2345	4.3730E-01	1
	BMI Penetration Nozzle	0.95	0.15	4.4763E-02	7.6615E-01	5.1443E-05	11
	Cold Leg Nozzle	0.95	0.15	4.4763E-02	7.2582E-01	4.8735E-05	12
	HotLeg Nozzle	0.95	0.15	6.1378E-01	6.7881E-01	6.2496E-02	7
	Safety Injection Nozzle	0.95	0.15	6.1378E-01	5.0231E-02	9.1926E-02	5
	Core Support Pads	0.95	0.15	4.4763E-02	1.1660	7.8292E-05	9
	Leak-off Monitor Holes	0.95	0.1	6.1378E-01	1.0451	6.4151E-02	6

KORI unit 1 PWSCC susceptibility indices were recalculated with normalization process and shown in Table. As seen in the Table, each factor in susceptibility index has a meaningful value of similar order of magnitude. The component ranking was found to change not so much by the normalization process.

4. Conclusions

Normalization process using a reference value or a threshold value was introduced in calculation of PWSCC susceptibility index. The result shows the meaningful value of similar order of magnitude, while the component ranking was not changed so much from the original Westinghouse model. It can be concluded that the normalization process can be implemented in Alloy 600 aging management program.

REFERENCES

[1] EPRI Project Manager (C. King), Material Reliability Program: Generic Guidance for Alloy 600 Management (MRP-126), p.33~34, November 2004.
[2] P.M Scott, Stress Corrosion Cracking in Pressurized Water Reactor – Interpretation. Modeling and Remedies, 2000 F.N Speller Award Lecture, p.3~6, November 2004.