

# 정규화된 PWSCC 민감도 지수를 이용한 Alloy 600 기기 검사 우선순위 선정

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## Alloy 600 Components Inspection Prioritization Using the Normalized PWSCC Susceptibility Index

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### ABSTRACT

Alloy 600 widely used in nuclear power plant is susceptible to primary water stress corrosion cracking (PWSCC). It is important to prioritize the inspection of Alloy 600 components using PWSCC susceptibility index. Plant-specific model for the susceptibility index was reviewed. The normalized PWSCC susceptibility index to a reference value is suggested and applied. The result was found to be reasonable.

**Key Words :** PWSCC(일차냉각수 응력부식균열), Susceptibility Index (민감도 지수), Prioritization of Inspection (검사 우선순위), Alloy 600, Residual Stress (잔류응력)

### 기호설명

- $F_m(I_m)$  = a material susceptibility factor  
 $F_s$  = a stress susceptibility factor  
 $F_T$  = a temperature susceptibility factor  
 $\sigma_a(\sigma)$  = the applied stress (*ksi*)  
 $\sigma_y$  = the yield stress of the material (*ksi*)  
 $k$  = the residual stress factor  
 $Q(E)$  = the activation energy of the material (*J/mol*)  
 $R$  = the universal gas constant (*8.314 J/mol*)  
 $T$  = the maximum temperature (*°K*) in which the Alloy 600 component has been operating.  
 $t_f$  = the initiation time of PWSCC (*hr*)

### 1. Introduction

Primary water stress corrosion cracking (PWSCC) of Alloy 600 is a well-known degradation mechanism nowadays in nuclear power plants. As understandable by its name, PWSCC is a phenomenon that a component made of particular material (i.e., Alloy 600, and its weld metal Alloy 82, 182) under tensile loading is very susceptible to corrosion in primary water environment in PWR.<sup>(1)</sup>

Fig 1 shows the typical Alloy 600 components in PWR. For the safe operation of a nuclear power plant, it is very important to properly manage the Alloy 600 components. The usual management program includes the inspection, monitoring and trend, acceptance criteria, preventive methods and corrective methods, etc.

Because there are many Alloy 600 components as seen in Fig. 1, the inspection prioritization scheme is based

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on the susceptibility index of the components to PWSCC.<sup>(2)</sup>

This paper reviews the PWSCC susceptibility index used in a Korean nuclear power plant<sup>(3)</sup>, and suggests a modification of the susceptibility index using threshold value.

## 2. PWSCC Susceptibility Index

### 2.1 Three factors affecting PWSCC susceptibility index

As mentioned earlier, PWSCC is a peculiar cracking occurred when three factors are met together, like susceptible material (Alloy 600) and stress (tensile stress) and corrosive circumstance (high temperature of primary water environment in PWR). Those factors may be determined by more detailed influencing factors such as:

- Material factors: material properties, metallurgical characteristics, material processing history, welding

method & process, repair history

- Temperature factors: operating history of the components in a certain temperature
- Stress factors : operational stress (due to pressure, mechanical and thermal stress etc.), fabrication residual stresses

### 2.2 Susceptibility index model suggested by Westinghouse

The susceptibility index used for the prioritization of inspection in the plant under investigation was Westinghouse model<sup>(3)</sup>, since the plant was constructed by the Westinghouse.

The Westinghouse model defines the PWSCC susceptibility index as:

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

As each factor can be obtained by numerical value,

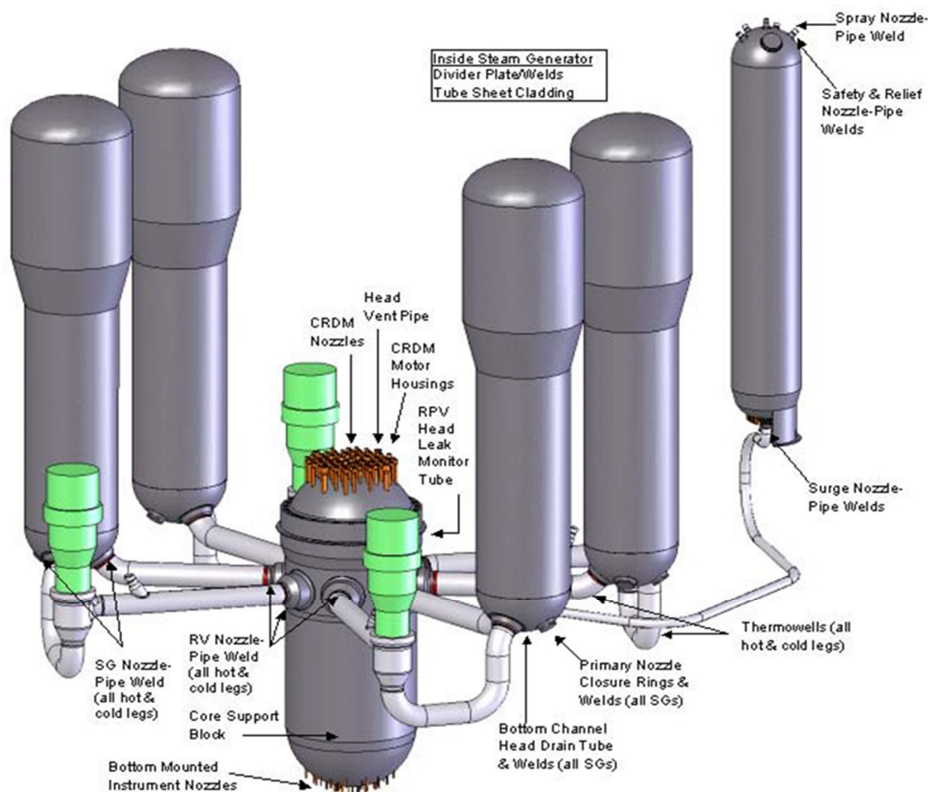


Fig. 1 Typical Alloy 600 components in PWR (reproduced from reference<sup>(4)</sup>)

Westinghouse model can give the quantitative  $SI$  which can be easily used for the prioritization of inspection. High number of  $SI$  means high priority.

$F_m$ , material factor has a value of from 0 to 1 according to the microstructure of the material. Table 1 shows the material factors.<sup>(1,3)</sup>

**Table 1.** Material factor,  $F_m$

Material	Shape	Manufacturing process	$F_m$
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 metal	As-welded	0.1
Alloy 182	Weld metal	As-welded	0.15

$F_s$ , as an effective stress factor can be expressed as below:

$$F_s = (\sigma_a + k\sigma_y)^4 \quad (if \ k < 1)$$

$$= (k\sigma_y)^4 \quad (if \ k \geq 1)$$

$k$  is the residual stress factor which can be determined according to the manufacturing process. Table 2 shows the residual factor.<sup>(3)</sup>

**Table 2.** Residual stress factor,  $k$

Area	Manufacturing process	$k$
Base metal/ Heat affected zone	Annealed condition	0
	As- manufactured (hot/cold worked)	$1 + \frac{7(ksi)}{\sigma_y}$
	Base metal nearby weld	0.5
Weld metal	As welded (no post weld heat treated)	0.95
	post weld heat treated	0.5
	Surface cold working after weld or final manufacturing	1.2
	Multiple weld cycles (including repair welding)	1.25

$F_T$ , as a temperature factor can be drawn by below equation.<sup>(2)</sup>

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

Synthesizing the above three factors, the susceptibility index ( $SI$ ) can be obtained for the Alloy 600 components.

Table 3 shows the results and the prioritized ranking for inspection.<sup>(3)</sup> Note that all data are plant-specific.

The results show that the top priority should be given to vent line nozzle weld metal, and the next one to control rod drive mechanism (CRDM) nozzle base metal.

### 2.3 Discussion on the SI results

Westinghouse model seems to be quite effective and convenient susceptibility analysis method. Based on the calculated  $SI$  value, Alloy 600 components are ranked to prioritize the expenditure of resources for inspection, the decision for mitigation and preventive actions, replacement of the component, and additional requirements for long term management program.<sup>(4)</sup>

The engineering unit of  $SI$  is the inverse of time (hour), because the Westinghouse model for PWSCC susceptibility index seems to be the inverse number of PWSCC initiation time-to-failure.

The initiation of PWSCC can be described by the well-known empirical equation for the estimation of time-to-failure proposed by Scott as follows<sup>(1)</sup>:

$$t_f = C \frac{\sigma^{-4}}{I_m} \exp\left(\frac{E}{RT}\right)$$

Comparing the two equations for  $SI$  and  $t_f$ , it is easily found that  $SI$  is conceptually the inverse of  $t_f$ .

As seen in Table 3, however, the calculated  $SI$  values are in the range of  $10^{-12} \sim 10^{-16}$  which are very small number. The temperature factor  $F_T$ , is relatively too small ( $10^{-19} \sim 10^{-20}$ ) when compared to the stress factor  $F_s$  (in the range of  $10^5 \sim 10^7$ ). It may mislead that the temperature factor has very little effects on the total susceptibility index. In general, the temperature is known to be the most influencing factor to PWSCC.<sup>(1,2)</sup>

In actual assessment of reactor vessel head to PWSCC susceptibility, United States Nuclear Regulatory Commission (USNRC) recommends that the temperature factor should

**Table 3.** SI results and ranking for inspection

Component	Part and Location	$k$	$F_m$	$F_s$	$F_T$	$SI$	Ranking
Reactor Vessel	Base Metal						
	CRDM penetration nozzle	1.1	0.5	1.2874E7	2.0337E-19	1.3090E-12	4
	Vent line nozzle	1.3	0.5	1.4909E7	2.0337E-19	1.5160E-12	3
	BMI penetration nozzle	1.3	0.4	1.5161E7	2.2575E-20	1.3690E-13	8
	Safety injection nozzle	0.5	0.25	9.1166E5	3.0972E-19	7.0590E-14	9
	Core support pads	0.5	0.25	1.3170E5	2.2575E-20	7.4326E-16	13
	Weld Metal						
	CRDM penetration nozzle	0.95	0.15	1.1584E8	2.0337E-19	3.5338E-12	2
	Vent line nozzle	0.95	0.15	1.2886E8	2.0337E-19	3.9310E-12	1
	BMI penetration nozzle	0.95	0.15	1.3455E7	2.2575E-20	4.5561E-14	10
	Cold leg nozzle	0.95	0.15	1.3173E7	2.2575E-20	4.4606E-14	11
	Hot leg nozzle	0.95	0.15	1.2320E7	3.0972E-19	5.7235E-13	6
	Safety injection nozzle	0.95	0.15	1.8121E7	3.0972E-19	8.4187E-13	5
	Core support pads	0.95	0.15	1.1572E7	2.2575E-20	3.9186E-14	12
	Leak-off monitor holes	0.95	0.15	1.0187E7	3.0972E-19	3.1551E-13	7

be normalized to  $600^\circ F$  when the effective degradation years is defined for the prioritization of inspection<sup>(2)</sup>, as follows:

$$EDY = \sum_{j=1}^n \left[ \Delta EFDY_j \exp \left\{ -\frac{Q}{R} \left( \frac{1}{T_{head}} - \frac{1}{T_{ref}} \right) \right\} \right]$$

Here  $EDY$  is the total effective degradation years,  $\Delta EFDY_j$  is each effective full power years operated at certain temperature  $T_{head}$ ,  $T_{ref}$  is the reference temperature ( $600^\circ F$ ). USNRC requires that all licensees shall assign the reactor vessel head at their facility to the appropriate PWSCC susceptibility category based on the  $EDY$  calculation; high ( $EDY > 12$ ), moderate ( $8 \leq EDY \leq 12$ ), low ( $EDY < 8$ ).

Another point to discuss is the engineering unit of SI. As mentioned earlier,  $SI$  has the engineering unit of inverse of time. Among three factors consisting  $SI$ , the temperature factor  $F_T$  is definitely dimensionless and the stress factor  $F_s$  has definitely stress dimension with power of 4. The material factor  $F_m$  seems to be originated from  $I_m$  in time-to-failure equation, which might be dimensionless. But in Westinghouse model for  $SI$ , the material factor  $F_m$  should have a complicate engineering

unit which may be physically meaningless. It is much comfortable to have all three factors dimensionless to make dimensionless  $SI$ .

### 3. Normalization of Susceptibility Index by Threshold Value

For dimensionless PWSCC susceptibility index, the normalization of both temperature factor and stress factor to certain reference values (or threshold value) is attempted in this paper.

#### 3.1 Normalization of temperature factor

USNRC's  $EDY$  concept is very good example to the normalization of temperature factor. The reference temperature value can be selected as the average temperature of primary water in nuclear power plant. Temperature of  $325^\circ C$  ( $598^\circ K$ ) was used for the re-calculation of  $SI$  such as:

$$F_t = \exp \left\{ -\frac{Q}{R} \left( \frac{1}{T} - \frac{1}{598} \right) \right\}$$

#### 3.2 Normalization of stress factor

For the normalization of stress factor, threshold value

can be used as follows:

$$F_s = \left( \frac{\sigma_{applied}}{\sigma_{threshold}} \right)^4$$

There must be existed the stress threshold below which PWSCC does not initiate. But unfortunately the test data for the stress threshold is very limited. Fig. 2 and 3 show the test data for stress threshold values, 400 MPa (58.0 ksi) for Alloy 600 base metal<sup>(5)</sup>, and 284 MPa (41.2 ksi) for Alloy 182 weld metal<sup>(6)</sup> respectively.

These values are to be used for the normalization of stress factor here, because the purpose of this paper is to review the prioritization of inspection for Alloy 600 components.

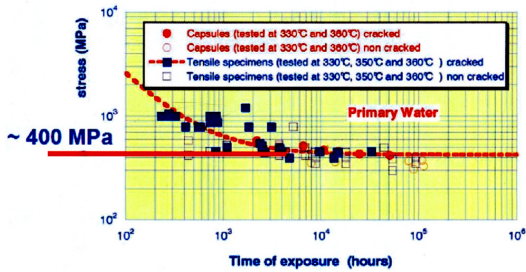


Fig. 2 Stress threshold value for Alloy 600 (reproduced from reference<sup>(5)</sup>)

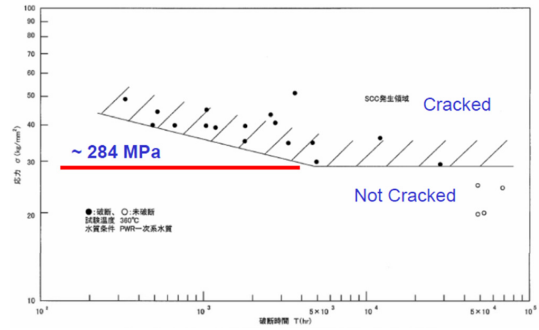


Fig. 3 Stress threshold value for Alloy 182 (reproduced from reference<sup>(6)</sup>)

### 3.3 Recalculation SI using Normalized Factors

Using the above three normalized factors, the susceptibility index (*SI*) was recalculated for the same Alloy 600 components. Table 4 shows the results and the adjusted priority ranking for inspection.

The numerical values of stress factor  $F_s$  at different parts and locations are quite diversified. Compared to the temperature factor  $F_T$ , the influence of stress factor cannot be negligible particularly for weld area in which the stress threshold value to initiate PWSCC is quite low. It was found that the priority for inspection was slightly changed accordingly from the original ranking in Table 3.

Table 4. Recalculated SI and ranking for inspection

Component	Part and Location	$k$	$F_m$	$F_s$	$F_T$	$SI$	Ranking
Reactor Vessel	Base Metal						
	CRDM penetration nozzle	1.1	0.5	1.1372	0.4030	0.3897	5
	Vent line nozzle	1.3	0.5	1.3174	0.4030	0.2121	7
	BMI penetration nozzle	1.3	0.4	1.3397	0.0447	0.0299	10
	Safety injection nozzle	0.5	0.25	0.0806	0.6138	0.0124	12
	Core support pads	0.5	0.25	0.0116	0.0447	0.0001	13
	Weld Metal						
	CRDM penetration nozzle	0.95	0.15	40.2040	0.4030	2.4303	2
	Vent line nozzle	0.95	0.15	44.7228	0.4030	2.7035	1
	BMI penetration nozzle	0.95	0.15	4.6698	0.0447	0.0313	8
	Cold leg nozzle	0.95	0.15	4.5719	0.0447	0.0307	9
	Hot leg nozzle	0.95	0.15	4.2758	0.6138	0.3937	4
	Safety injection nozzle	0.95	0.15	6.2892	0.6138	0.5790	3
Core support pads	0.95	0.15	4.0162	0.0447	0.0269	11	
Leak-off monitor holes	0.95	0.15	3.5355	0.6138	0.3255	6	

#### 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 *SI* value of similar order of magnitude, while the component ranking was slightly changed from that in the original Westinghouse model.

As expected, the weld metal area is found to be much susceptible to the initiation of PWSCC than the base metal. Therefore it is quite reasonable to give the priority for inspection weld area first. It should be noted that the results are plant-specific.

#### Acknowledgements

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