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Mechanisms of Flow Accelerated Corrosion in CANDU Feeder Piping

Jun Hwan Kim and In Sup Kim

Korea Advanced Institute of Science and Technology
Department of Nuclear Engineering
373-1 Kusong-dong, Yusong-gu
Taejon, Korea 305-701

Abstract

Wall thinning caused by Flow Accelerated Corrosion (FAC) in CANDU feeder piping was calculated using WATHEC and modified WATHEC code. Possible FAC mechanisms were discussed. Finally, to correct positional as well as velocity dependency, modification of the model was introduced and compared to the actual wall thinning data.

I. INTRODUCTIONS

Flow Accelerated Corrosion (abbreviated as FAC) phenomena have been investigated and studied since the accident of Surry steam line failure[1]. Researchers have mainly focused on the degradation of the secondary piping in PWR[1,2,8]. FAC processes and on-line monitoring techniques are now being established well. Whereas FAC problem in

CANDU was not emerged until the Point Lepreau feeder leak accidents happened. After AECL's recommendation for periodic monitoring wall thickness, Wolsong Unit 1 and 2 reported same problem related to FAC. The objectives of this paper are calculation of the thinning rates based on the WATHEC and modified WATHEC code and description of their related mechanisms on CANDU.

II. CALCULATION OF FEEDER WALL THINNING RATES

1. WATHEC and Modified WATHEC code

1-1 WATHEC code

WATHEC (WAll THinning due to Erosion Corrosion) code was developed by Heitmann and Kastner to evaluate the thinning rate in German plant[3]. Their results were based on the data of the BENSON test rig in KWU. Their predicted model is consisted the multiplication of independent number of factors such as pH, dissolved oxygen, velocity, alloying contents. The allowable boundaries of the model are;

Velocity	:	$5 \leq v \leq 38.8$ (m/sec)
Temperature	:	$50 \leq T \leq 240$ (°C)
pH	:	$6.8 \leq pH \leq 9.5$
Dissolved oxygen	:	$0.46 \leq g \leq 505$ (ppb)

The predicted results derived by the model will be somewhat overestimated because input temperature and pH are lower than typical CANDU conditions.

1-2 modified WATHEC code

Modified WATHEC code[4] was developed in MIT. It is incorporated into the analysis of literature and the functional dependencies in the previous WATHEC code. Types of the modifications include the decoupling of velocity and alloying element content at low alloying element content, elimination of the effect of oxygen for bulk oxygen concentration below a critical value, and an improvement in the two-phase correlation used to estimate liquid phase velocity.

2. Input data

The Input data to estimate the thinning rate were followed as CANDU primary heat transport condition. They are shown in table 1. Note again that the input pH was slightly lower than actual value for the limitation of the model.

3. Results

Figure 1 shows the FAC thinning rates in CANDU feeder conditions as a function of temperature. The curve shows a typical bell-shaped curve. Figure 2 shows on the thinning rate as a function of velocity compared to the actual results of Point Lepreau data. It reveals that data which predict on the basis of PWR code show velocity-insensitive manner whereas actual data show highly velocity-sensitive trends with a power of 1.52[5]. Although input data were more severe than CANDU conditions, the conventional PWR code shows less thinning rates than actual CANDU value.

III. DISCUSSIONS

1. Descriptions of FAC phenomena

FAC is a process in which protective oxide layer on carbon or low-alloy steels dissolves into a steam of flowing water or a water-steam mixture. The oxide layer becomes thinner and less protective, and the corrosion rate is increased. Eventually a steady state is reached where the corrosion and dissolution rates are equal and the stable corrosion rates are maintained. A thinned component will typically fail due to overstress from operating pressure or abrupt changes in conditions such as waterhammer, start-up loading etc. It is generally accepted that the FAC process is divided into the two subsequent processes. The first process is the production of soluble ferrous ions at the oxide-water interface, the second process is the transfer of the ferrous ions into the bulk water across the diffusion boundary layer. Parameters acting the first process and second process are various. The former reflects mainly solution pH, dissolved oxygen, soluble impurities and the latter represents flow velocities, local turbulence, dissolved ferrous ion gradient etc. Figure 3 shows the schematic representation of the FAC process. The characteristic of bell-shaped curve mentioned in the previous part is due to the rate determining steps of each process. At points below the maximum temperature, dissolution controls the whole process, while mass transfer reaction dominates at higher temperature. As shown from figure 2, Modified WATHEC code shows higher thinning rates than conventional WATHEC code. Because modified WATHEC code includes severities in lower alloying contents, where conventional WATHEC code overlooks the effect of lower alloying contents such as Cr and Mo[4].

2. FAC process in CANDU

The feeder is the primary heat transport component in which connects pressure tube and steam generator. Their characteristics of higher temperature, higher pH value seem to be far from the FAC compared to the feedwater corrosion in PWR[5]. Nevertheless, Point Lepreau Power Plant has experienced heavy water leak at the first bend of the outlet feeder[5]. After the accidents, same problem emerged at the Gentilly-2 and Embalse. Wolsong Unit 1 now suffers wall thinning at maximum rate 31.5% at a point similar to the Point Lepreau in 1997[7].

3. Possible FAC mechanisms in CANDU feeder

3-1 Selective dissolution along different metallographic boundaries

Microstructural observation of FAC-damaged surface often shows the preferential attack at the ferrite-pearlite interface. Figure 4 illustrates the selective attack on pearlite phase. Many authors have reported such phenomenon [1,8,9]. The mechanisms of such preferential attack are not completely investigated yet. Some authors suggested the differences of hydrogen diffusion, in which cause to initiate local cathodic reaction between ferrite and pearlite[10], other authors reported the local hardness differences between two different microstructures[11]. AECL analyzed failed feeder specimen taken from Point Lepreau through the SEM/EDX examination and reported that crack paths were entirely intergranular, most of them followed the ferrite grain boundaries. They temporarily concluded that Strain-Induced Corrosion Cracking (SICC) caused by the inadvertent thermal impact during reactor startup and refueling outages was the most plausible mechanism[7].

3-2 Oxide spalling

Conventional FAC description is based on the assumption that protective oxide thins continuously during fluid flows. Such assumption has a limitation that the velocity dependence can be no greater than correlation dictated by the fully mass transfer. The function of velocity will be a maximum power of 0.86 at mass transfer dominated region. This is mainly due to the fact that Sherwood number is a function of Reynolds number with a power of 0.86 at fully mass transfer controlled condition[12]. To avoid this limitation and to produce a mechanism that can explain a high velocity dependence as mentioned in figure 2, Lister[5] postulated a synergism between dissolution and erosion. As corrosion proceeds and the oxide dissolution process continues, the film gets progressively weaker, eventually, the fluid shear forces overcome the cohesive forces in the oxide and subsequent spalling occurs. Scalloped surfaces are created by the erosion and combined dissolution processes. He reported that velocity dependence nature was appeared and comparison of actual data showed a good agreement.

3-3 External erosion contribution

One of the limitations of the above model is that it does not include the variation of flow directions. If the wall thins by the mechanism of oxide spalling only, wall thinning will be the same rate regardless of the inlet and outlet side of the feeder position. Actually, report[5] has it that outlet feeders are corroding much more rapidly than inlets. It also mentioned that all of three inlet feeders that were measured indicated corrosion averaged over the lifetime below 20μm/yr, whereas the outlets indicated rates up to

150μm/yr. Also it does not explain consistently the role of oxide. If we extend to the model at lower temperature, in which dissolution and mass transfer simultaneously take place, it will show rather a overestimated value in case of the high fluid velocity. Thus, to explain spatial dependence as well as velocity-sensitive trends we introduce external erosive factors, such as erosive action of flowing oxide scale, cavitation of microbubbles producing at the outlet of feeders, and corrosion products produced in pressure tube by internal corrosion. If we introduce velocity enhancement factor taking into account of such external erosion contributions into the model, the above correlation can be modified as follows;

$$\dot{m} = F_1(T, allcont, v) \cdot F_2(pH) \cdot F_3(O_2) \cdot F_4(G) \cdot F_5(e)$$

F_5 denotes the term related to the dimensionless erosive factor which includes the following electrochemical variables;

$$F_5(e) = \frac{i_{diss}(erosion)}{i_{diss}(corros.)}$$

Velocity enhancement data in this paper were adapted to the erosion of mild steel in carbonate-bicarbonate solutions where $i_{diss}(erosion)$ is dissolution current in the presence of erosive medium and $i_{diss}(corros.)$ means dissolution current in pure corrosion condition[13]. Figure 5 shows the modification of the model compared to the Point Lepreau feeder leak data. Although the results seem to be somewhat overestimated because of slight differences of the electrochemical system between actual system and literature, velocity dependence appeared and it followed similar trends. Moreover it explains thinning rate differences between inlet and outlet because external erosive action at outlet tends to be more significant than inlet as the fluid flows. Further erosion-related electrochemical data will be needed for developing the model in the next study.

IV. CONCLUSIONS

1. Wall thinning rates were calculated using WATHEC and modified WATHEC code in CANDU primary heat transport conditions. Slow velocity dependence was shown in the model results whereas actual feeder data are a function of velocity with a power of 1.52. These inconsistencies resulted from the assumption of steady state magnetite dissolution at conventional PWR model.

2. Possible FAC mechanisms were discussed. They are selective dissolution between ferrite and pearlite microstructures, oxide spalling and its related enhanced dissolution, external erosive effects

3. Modification of the PWR model to correct both of velocity and spatial dependence was introduced and compared to the actual feeder thinning data. Although the modification seems somewhat overestimated, same velocity trends were derived. Further erosion-related experiment will be needed for the reinforcement of the model.

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Table 1 Specification of input data and actual condition

	WATHEC	Point Lepreau
Temperature	513K(240°C)	581K(308°C)
pH	9.2	10.6
Dissolved Oxygen(ppb)	4	4
Material spec	SA106 Gr.B	SA106 Gr.B
	(Cr+Mo=0.03%)	(Cr<0.03%)
Geometrical factor	90° bending	first bend (106.2°)

Table 2 Data of dimensionless erosive factors [13]

Variables	value
i_{diss}(erosion)	$0.5889 \times v^{0.87}$
i_{diss}(corros,)	$0.6456 \times v^{0.48}$
f	0.5012

f used as a multiplication factor to correct pH to CANDU condition [14]

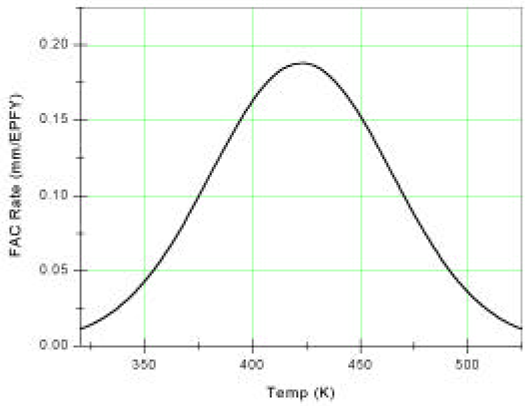

Figure 1. Material loss as a function of temperature in CANDU condition

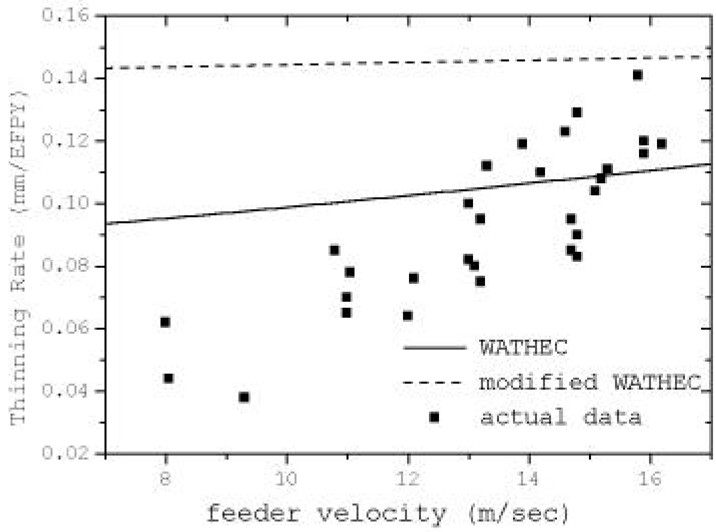

Figure 2. WATHEC and modified WATHEC code and actual data of Point Lepreau

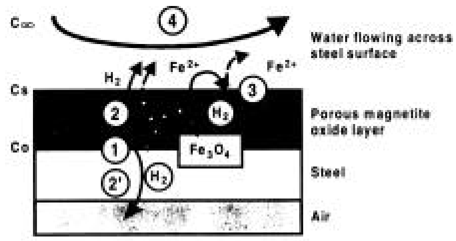

Figure 3. Typical FAC process

Figure 4. Selective attack on the pearlite phase on a carbon steel surface[1]

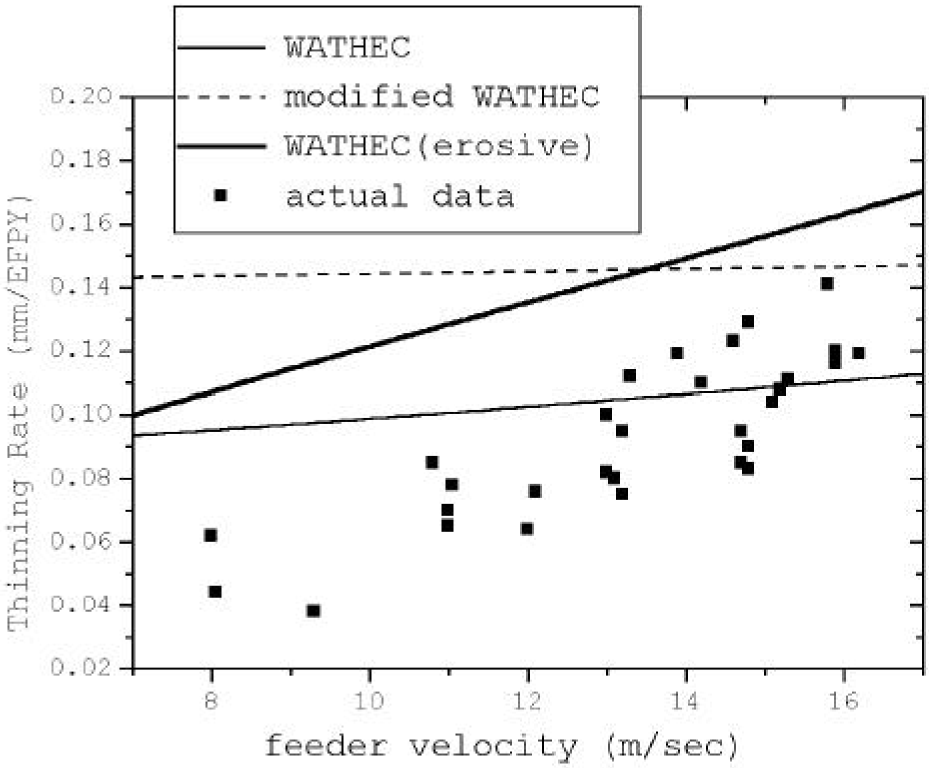

Figure 5. Erosive modification and comparison of each data