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EVALUATION METHOD FOR PIPE WALL THINNING DUE TO LIQUID DROPLET IMPINGEMENT - (I) OVERVIEW

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Abstract

The analysis code system, DRAWTHREE-LDI has been developed in order to evaluate pipe wall thinning due to liquid droplet impingement (LDI). The wall thinning due to LDI is classified into two types which are LDI (corrosion) and LDI (erosion). In LDI (corrosion), the dominant mechanism to dwindle pipe wall thickness is flow-accelerated corrosion which is a chemical process. While in LDI (erosion), it is impact onto wall surfaces due to droplet impingement which is a physical process. The comparison between results calculated by DRAWTHREE-LDI and those measured at an actual power plant shows good agreements within a factor of two.

Introduction

The pipe wall thinning caused due to liquid droplet impingement (LDI) is one of the major concerns for nuclear and fossil power plants to improve their capacity factors and to extend their lifetimes. In order to evaluate wall thinning due to LDI, an analysis code system DRAWTHREE-LDI has been developed, followed by validations on it [1].

The purpose of this article to explain the methodology adopted in DRAWTHREE-LDI and to make a validation on it.

In DRAWTHREE-LDI, the wall thinning due to LDI is classified into two types, LDI (erosion) and LDI (corrosion) [1]. The evaluation methodology adopted in DRAWTHREE-LDI is explained in detail.

In order to validate DRAWTHREE-LDI, comparisons will be made between the results calculated by DRAWTHREE-LDI and those measured in feedwater heater drain systems at an actual power plant.

1. Evaluation procedure for LDI (erosion) and LDI (corrosion)

Major phenomena regarding pipe wall thinning under single- and two-phase flow conditions are shown in Fig. 1. Under a single-phase flow condition, pipe wall thinning is caused due to flow-accelerated corrosion (FAC), typically observed in the downstream of orifices, valves, and bends where turbulence is likely to be generated. Against pipe wall thinning due to FAC, chemical control measures have been applied to water cooling systems. Under a two-phase flow condition, on the other hand, droplet behaviour play a dominant role in pipe wall thinning. In turbine extraction lines, tiger strip pattern corrosion was observed due to droplet periodic collisions onto the pipe wall, as shown in Fig. 1. This type of corrosion was mitigated by replacing pipe wall material from carbon steel to low alloy steel in which the weight concentration of chromium is greater than 0.2 %. In feedwater heater drain systems, shotgun pattern corrosion is observed at bends of piping, as shown in Fig. 1. Replacements of piping material were not effective in order to mitigate this type of pipe wall thinning.

This article presents the methodology to evaluate pipe wall thinning due to LDI observed at bends in feedwater heater drain systems. The LDI is classified into two categories, that is, LDI (erosion) and LDI (corrosion) [1].

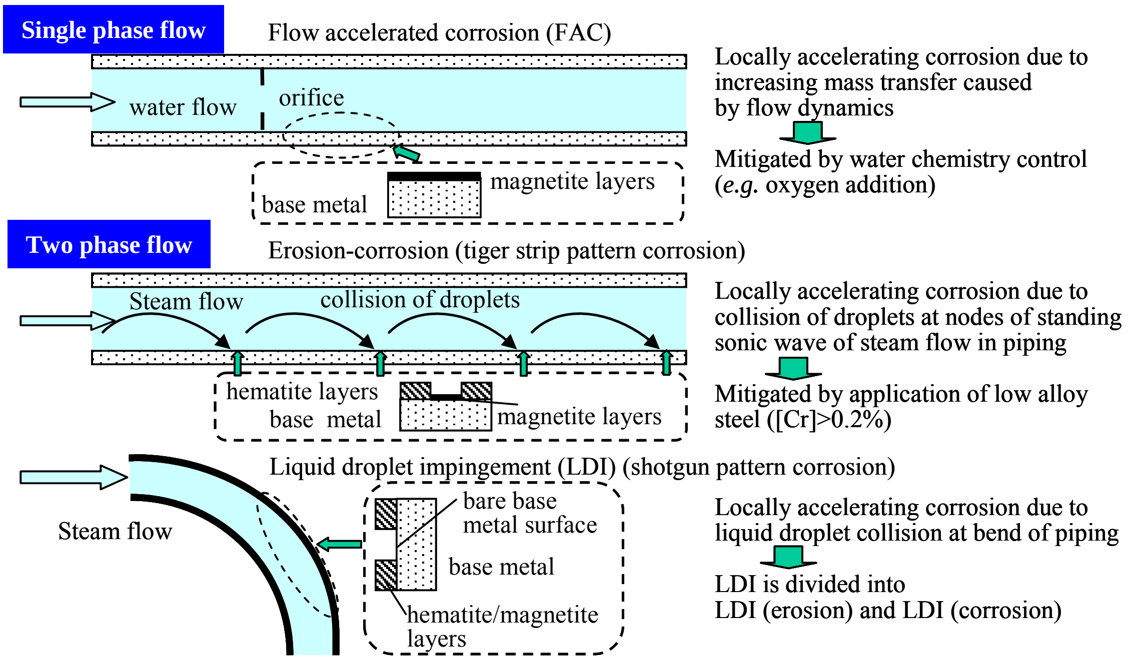

Figure 1 Major phenomena of wall thinning under single- and two-phase flow conditions.

In Fig. 2, FAC/LDI risk zones are depicted with a flow regime pattern. The vertical axis corresponds to quality. Upper and lower horizontal axis correspond to steam flow velocity and water flow velocity, respectively. The flow regime with a quality of zero corresponds to a single-phase flow. LDI (corrosion) is likely to occur in the regime with steam flow velocity smaller than ~100 m/s. In the regime with steam flow velocity greater than ~100 m/s, LDI (erosion) is likely to occur.

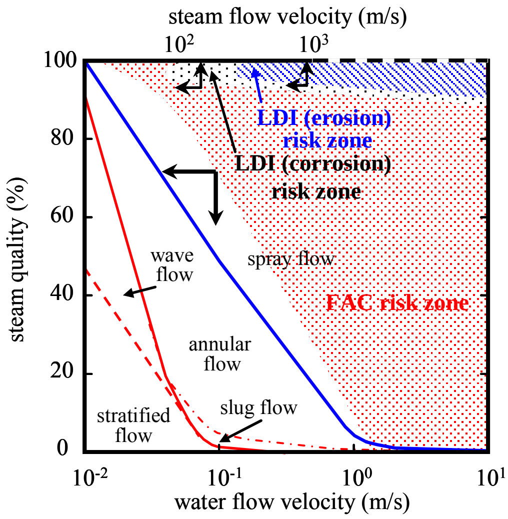

Figure 2 Conceptual flow regime pattern and FAC/LDI risk zone under single- and two-phase flow conditions.

Schematic diagram of interaction of droplets with pipe wall is shown in Fig. 3. The interactions are classified into three categories:

- zone (zone I) with no droplet collisions,
- zone (zone II) with droplet collisions, and
- zone (zone III) with liquid film covering on the pipe wall.

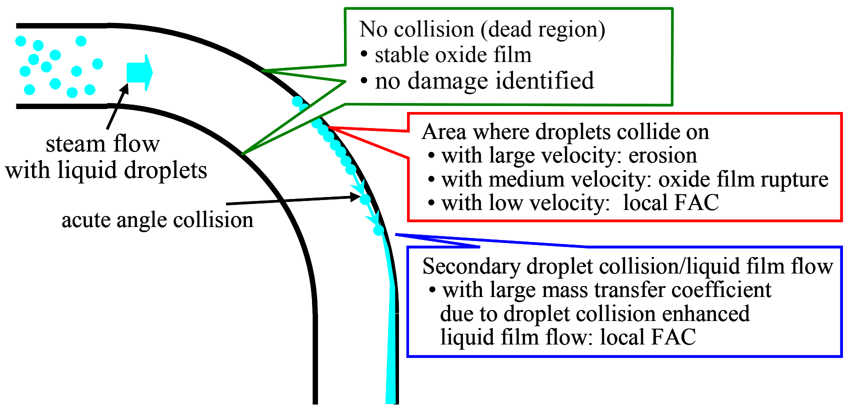

Figure 3 Schematic diagram of interaction of droplets with pipe wall

In the zone I, there are no damages because there are no droplets impinging on the pipe wall. The pipe wall with oxide films generated on the surface remains intact. In the zone II, droplet impingements with high velocities cause physical erosion of the pipe wall or oxide films generated on the surface, corresponding to LDI (erosion). With low velocities, physical erosion due to droplet impingements are not caused, however, wet condition generated by droplets potentially causes local

FAC, corresponding to LDI (corrosion). In the zone III, stable liquid film flow on the surface generated by droplet collisions potentially enhances local FAC, corresponding to LDI (corrosion).

In order to identify zones where pipe wall thinning due to LDI is likely to occur, major parameters contributing to LDI are identified as shown in Fig. 4. The parameters are classified into four groups: flow pattern, corrosive conditions, impingement parameters, and materials, as shown in Fig. 4. The necessary conditions for LDI occurrence is designated as overlapping conditions of each LDI risk zone.

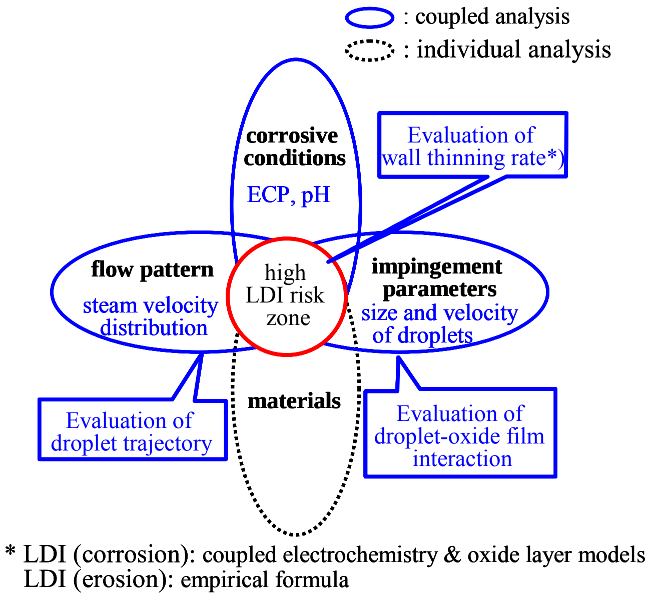

Figure 4 LDI risk zone indicated by major parameters.

The evaluation procedure consists of six steps as shown in Fig. 5. In step 1, 3D flow dynamics calculations are made to obtain mass flow velocity and quality in the piping. Under the flow conditions calculated in step 1, droplet trajectories are tracked in step 2. In step 3, LDI patterns are evaluated based on droplet number density and velocity colliding on the pipe wall which are calculated in the previous step 2. In step 4, the occurrences of LDI (erosion) and LDI (corrosion) are evaluated. Wall thinning rates are calculated according to each LDI model in step 5. For LDI (erosion), wall thinning rates are calculated by means of empirical formula obtained by Heymann [2]. For LDI (corrosion), the wall thinning model originally developed for FAC [3-6] is adopted. Finally, in step 6, residual lifetime and/or effectiveness of countermeasures are evaluated.

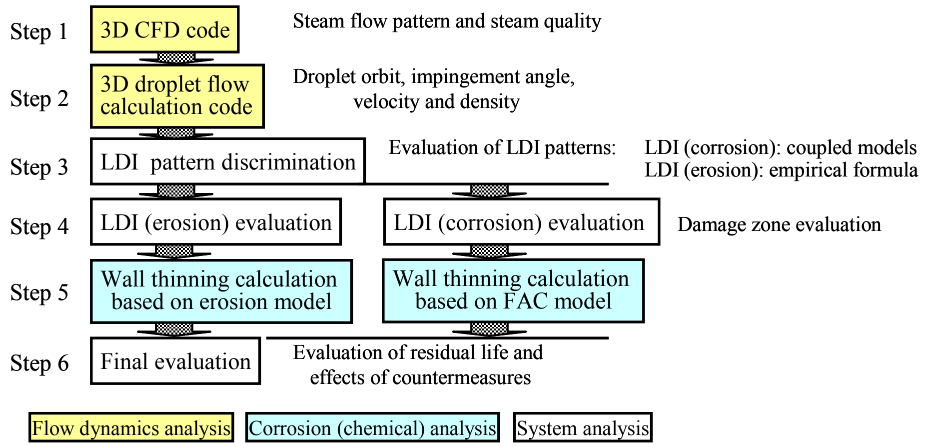

Figure 5 Evaluation steps for LDI.

The FAC evaluation model applied to LDI (corrosion) is composed of the electrochemistry model coupled with the oxide layer growth model, tabulated in Table 1 [2-5]. The electrochemistry model provides anodic/cathodic current densities and electrochemical potential (ECP) based on oxide film thickness and oxide properties. On the other hand, in the oxide layer growth model, oxide film thickness and oxide properties are calculated based on anodic/cathodic current densities and ECP which are calculated according to the electrochemistry model. Wall thinning rates due to FAC is calculated by means of the models coupled with each other, as listed in Table 1.

Table 1 Wall thinning rate calculation based on the electrochemistry model coupled with oxide layer growth model

Sub-model	Electrochemistry model (static model)		Oxide layer growth model (dynamic model)
Input	Temperature, $[O_2]$, pH, k_m, Mass transfer coefficient (h_m) Oxide film thickness, Oxide properties	Coupling calculation	Temperature Anodic/cathodic current densities ECP
Output	Anodic/cathodic current densities Electrochemical corrosion potential (ECP)		Oxide film thickness Oxide properties (Fe_2O_3/Fe_3O_4 ratio)
Final output	Anodic/cathodic current densities Wall thinning rate		

In order to evaluate pressure onto pipe wall generated due to droplet impingement, Moving Particle Semi-implicit for All Speed (MPS-AS) method [7] is adopted. Figure 6 shows calculated results of pressure transient generated on the pipe wall due to droplet impingements [8-10]. As a typical example observed in feedwater heater drain systems, droplet diameter is set to be 50 μm with collision velocity of 200 m/s. The existence of liquid film with thickness of 5 μm reduces the pressure about 2/3 times of that without liquid film.

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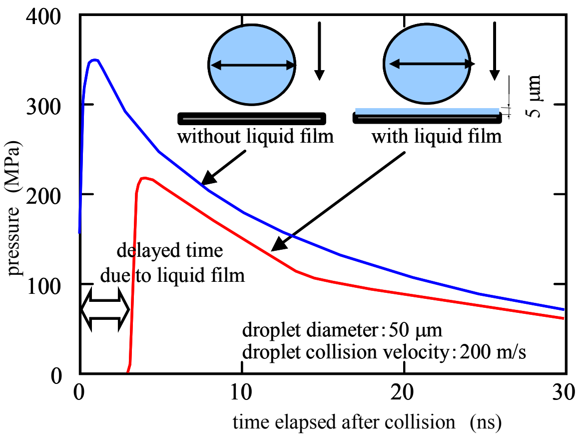

(4)

Figure 6 Pressure transient on the pipe wall with/without liquid film.

Empirical or theoretical formulae have been reported for pressure generated on pipe wall due to droplet impingements.

Heymann's formula [11]:

$$P = 3\rho_D C_o V_r \qquad \text{for } 0.03<V_r/C_o<0.3, \qquad (1)$$

$$P = \rho_D C_o V_r\ (2+(2k-1)V_r/C_o) \qquad \text{for } V_r>0.3,$$

Cook's formula [12]:

$$P = \rho_D C_o V_r\ (1+kV_r/C_o), \qquad (2)$$

Rochester & Brunton's formula [13]:

$$P = 0.7\rho_D C_o V_r, \qquad (3)$$

where the notations are as follows: P:pressure (Pa), ρ_D:droplet density (kg/m^3), C_0:sound velocity in steam (m/s), V_r:droplet collision velocity (m/s), and k:constant (-) (=2.0 for water).

Comparison of results calculated by means of Eqs. (1)-(3) with those calculated by MPS-AS method, as shown in Fig. 7, it is suggested that Heymann's formula can be applied to the estimation on the pressure generated on the pipe wall due to droplet impingement.

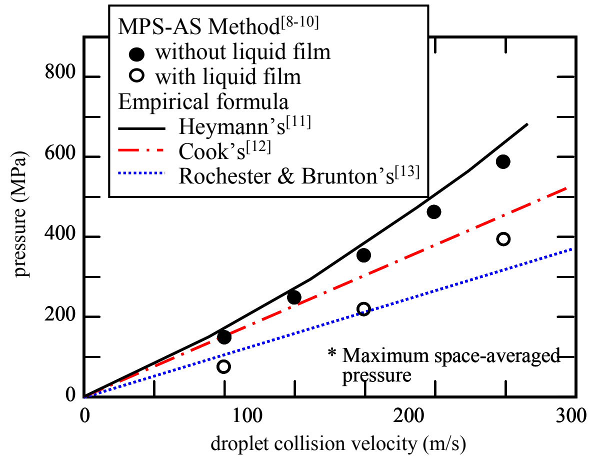

Figure 7 Comparison of pressure between the existing formulae and calculated results.

The wall thinning rate is evaluated by the empirical formula proposed by Heymann, which is shown in Eq. (4).

$$\log(Re) = 4.8\log(V_r) - \log(NER) - 16.65 + 0.67\log(d_p) + 0.57J - 0.22K, \quad (4)$$

where the notations are as follows: Re: rationalized erosion rate (m^3-eroded materials/m^3-collided droplet), NER: erosion resistance number , d_p: droplet diameter (m), J: constant (-) (0 for liquid droplet impingement), and K: constant of geometry (-) (0 for plane surface, 1 for curvature). The wall thinning rates evaluated by Eq. (4) are plotted as a function of droplet collision velocity in Fig. 8. Generally, wall thinning due to LDI (erosion) dominates in the region with droplet velocities greater than 150 m/s.

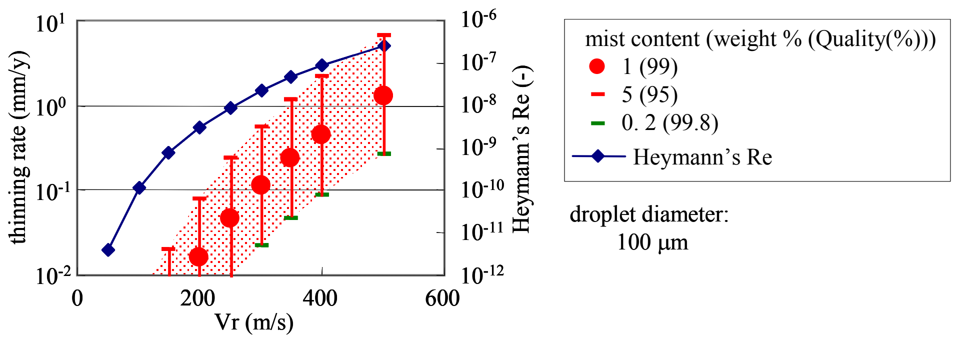

Figure 8 Wall thinning rate evaluated by Heymann's formula.

The wall thinning rates due to LDI (corrosion) are plotted as a function of mass transfer coefficient in Fig. 9. The mass transfer coefficients are evaluated by flow dynamics calculations in step 1 shown in Fig. 5. Raising values of pH reduces wall thinning rates though the oxygen concentration is quite low.

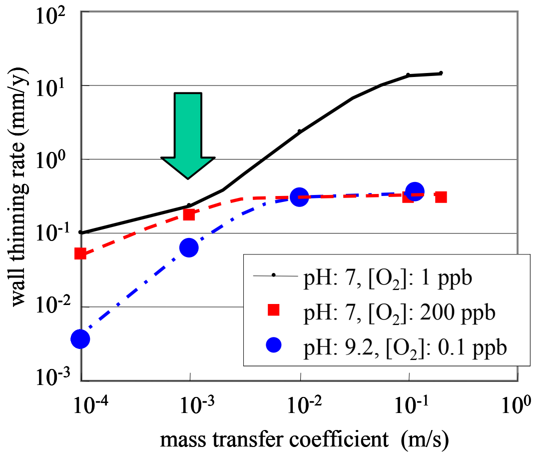

Figure 9 Wall thinning rate calculated due to LDI (corrosion) as a function of mass transfer coefficient.

The wall thinning rates due to LDI are plotted as a function of steam velocity in Fig. 10. In the region with low steam velocities, wall thinning rates are determined by LDI (corrosion). As steam velocities rises, the contribution by LDI (erosion) increases and becomes greater than that by LDI (corrosion) in the high steam velocity region. LDI (corrosion) is affected by the environmental factors, i.e., pH and oxygen concentration in the water. The major parameters affecting LDI (erosion) are droplet diameter and density colliding on the pipe wall. In the region with the steam velocity greater than ~150 m/s, LDI (erosion) is dominant to cause pipe wall thinning.

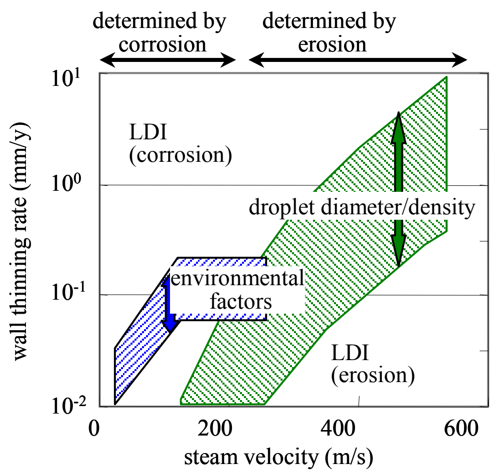

Figure 10 Schematic diagram of wall thinning rate due to LDI (corrosion) and LDI (erosion) as a function of steam velocity.

2. Evaluation on wall thinning rates

In order to validate DRAWTHREE-LDI, comparisons are made between the results calculated by means of DRAWTHREE-LDI and those measured in the feedwater heater drain systems at an actual power plant. The piping configuration and detailed calculation results are discussed in Ref.[14]. In this article, the comparisons are shown briefly.

The comparisons are made in the region where LDI (erosion) or LDI (corrosion) is dominant in the wall thinning of the piping. Each comparison is shown in Fig. 11(a) and (b). Their standard deviations are shown with the error bars. Figure 11 shows that the results calculated almost agree with those measured within a factor of two.

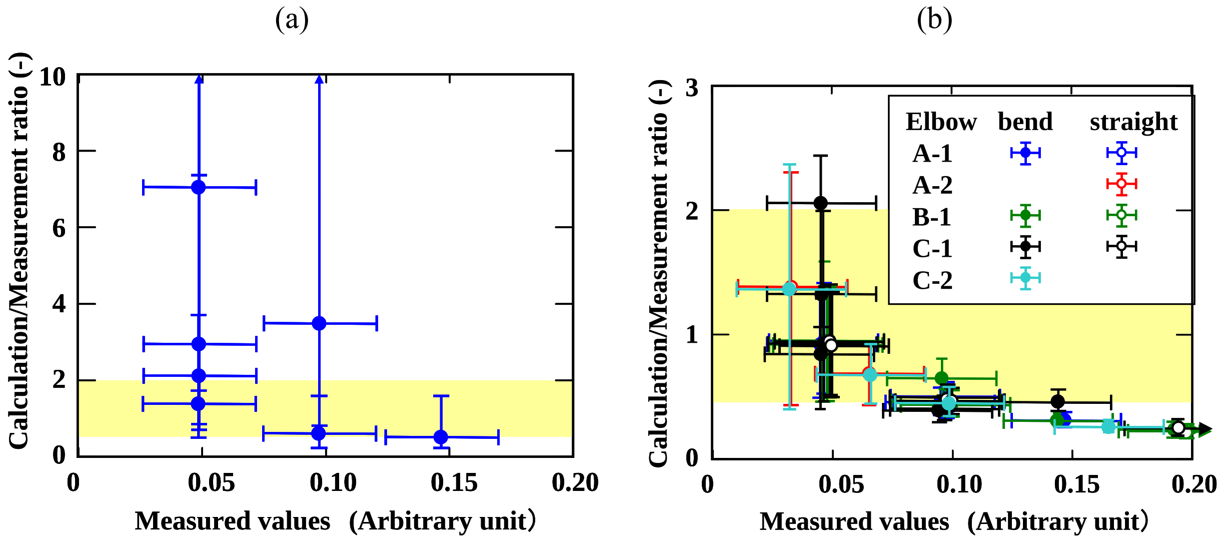

Figure 11 Comparison of values calculated with those measured at an actual plant for (a) LDI (erosion), and (b) LDI (corrosion).

3. Conclusion

In order to evaluate wall thinning due to LDI, the analysis code system DRAWTHREE-LDI was developed and validated through the comparison of results calculated with those measured at an actual power plant.

In DRAWTHREE-LDI, the wall thinning phenomena due to LDI is classified into LDI (erosion) and LDI (corrosion). The wall thinning rate due to LDI (erosion) is evaluated by means of the formula proposed by Heymann. The wall thinning rate due to LDI (corrosion) is evaluated by the electrochemistry model coupled with oxide layer growth model, which is applied to the wall thinning due to FAC. In DRAWTHREE-LDI, wall thinning is evaluated by the procedure composed of six steps.

As a validation on DRAWTHREE-LDI, the comparison was made between the results calculated by DRAWTHREE-LDI and those measured in the feedwater heater drain system at the actual power plant. The comparison shows that the both results almost agree within a factor of two.

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