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Axial Offset Anomaly (AOA) Risk Assessment at Various Plant Operating Conditions

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Abstract

An analytical evaluation of mass evaporation rate at various plant operating conditions was performed to find the best guideline of AOA risk assessment. For the specific $\dot{m}_e$ calculation, KSBOIL code was selected as an evaluation tool. The analytical model of $\dot{m}_e$ in KSBOIL code is similar to models proposed by Bowring and Griffith. The $\dot{m}_e$ was calculated by the KSBOIL code using a single channel model with various plant operating parameters. From the calculated results, it is concluded that the mass evaporation rate, $\dot{m}_e$ must be considered to be as an indicator of AOA risk for Korean Westinghouse type PWR plants. For the conservatism of $\dot{m}_e$ calculation, the measured RCS flow and design inlet temperature should be used to assess AOA risk. The sensitivity factors of $\dot{m}_e$ were roughly calculated to be 4.18 for core power, 13.52 for inlet temperature and -3.11 for RCS flow. Therefore, the plant operating parameters and peaking factors should be properly considered to minimize AOA risk in any changes of reactor core condition.

1. Introduction

The occurrence of Axial Offset Anomaly (AOA) is a limiting operational condition preventing many PWR plants from operating with efficient core designs. AOA occurs when boron incorporates in corrosion products deposited in the steaming regions of high-duty fuel assemblies causing the reactor neutron flux to be skewed. The AOA phenomenon is believed to result from three interrelated aspects: 1) subcooled boiling on high-duty assemblies, 2) enhanced corrosion product deposition on those rods, 3) boron is incorporated in those deposits causing a depression in neutron flux.

A number of Korean and overseas Westinghouse type PWR plants are experienced AOA risk during several operating cycles. The mass evaporation rate is generally considered to be the best indicator of AOA risk, although there are many other factors that come into play.

The mass evaporation rate ($\dot{m}_e$) is defined as the boiling heat flux at a point in the core divided by the latent heat of evaporation. The boiling heat flux is the difference between the total local heat flux defined by the partial boiling curve and the one defined by forced convection curve. The $\dot{m}_e$ is used as a correlating factor along with the plant coolant chemistry data to determine the possibility of the occurrence of the axial offset anomaly in the core, in which the power in the top portion of the core is depressed when it was compared to prediction. It is thought that high mass evaporation rate and relatively high impurity levels cause excessive crud formation in the top of the core. Boron could then be concentrated in this crud layer causing local power depressions and thus the axial offset anomaly.

The $\dot{m}_e$ should be evaluated whenever there is a change in plant operating conditions that could cause it to increase. The reactor power uprating is typical example of the significant change of plant operating parameters such as core power, flow, temperature, pressure and peaking factors. As an analytical tool, KSBOIL code[1] developed by Westinghouse Inc. is used. The $\dot{m}_e$ is calculated by the KSBOIL code using a single channel model with various plant operating parameters.

The purpose of this study is to find the sensitivity of $\dot{m}_e$ associated with the each plant operating parameter. And then, the calculated $\dot{m}_e$ value is used to be compared to plants which are in the $\dot{m}_e$ range where the AOA was observed or was expected. As the results of the $\dot{m}_e$ evaluation, the guideline relative to the variations in plant operating parameter is suggested to prevent the AOA risk under the current reactor operating condition.

2. Analytical Method

2.1 Definition of Mass Evaporation Rate

The mass evaporation rate model used in KSBOIL code is similar to models proposed by Bowring and Griffith[2]. The model assumes that heat is transferred by two mechanisms, single phase convection and boiling evaporation.

$$q''_{Total} = q''_{Convection} + q''_{Boiling} \quad (1)$$

The forced convection heat flux can be written:

$$\begin{aligned} q''_{Convection} &= h(T_W - T_B) \\ &= h(T_W - T_{Sat}) + h(T_{Sat} - T_B) \\ &= h\Delta T_W + h\Delta T_B \end{aligned} \quad (2)$$

where,

h = forced convection heat transfer coefficient

T_W = wall temperature

T_B = local bulk fluid temperature

T_{Sat} = saturation temperature

ΔT_W = $T_W - T_{Sat}$

ΔT_B = $T_{Sat} - T_B$

Thus, the boiling heat flux is easily determined from equation (1) and (2). To calculate the forced convection heat transfer coefficient, Dittus-Boelter correlation[2] with an adjustment factor to account for rod bundle effects is used in KSBOIL code. T_W is determined using an interpolation formula proposed by Bergles and Rohsenow[3] shown in Figure 1. The formula is:

$$q''_{Total} = q''_{Convection}\left[1 + \left[\frac{q''_{FDB}}{q''_{Convection}}\left(1 - \frac{q''_{Bi}}{q''_{FDB}}\right)\right]^2\right]^{1/2} \quad (3)$$

where,

q''_{FDB} = heat flux for fully deveoped boiling

Thom's correlation[4], in British Engineering Units, is used to model the heat flux for fully developed boiling.

$$q''_{FDB} = \left(\frac{1}{0.072}\, e^{P/1260}\right)^2 (\Delta T_W)^2 \quad (4)$$

q''_{Bi} is the heat flux from the equation (4) for fully developed boiling evaluated at the ΔT_W corresponding to the intersection of the forced convection and boiling inception curves shown in

Figure 1. This temperature difference is denoted as $\Delta T'_W$. Therefore:

$$q''_{Bi} = \left(\frac{1}{0.072} e^{P/1260} \right)^2 (\Delta T'_W)^2 \tag{5}$$

The heat flux at inception of boiling[2] is given by:

$$q''_i = \left(\frac{h_{fg}\, k}{8\, \sigma T_{Sat}\, \nu_{fg}} \right) (\Delta T'_W)^2 \tag{6}$$

where,

h_{fg} = latent heat of evaporation

k = thermal conductivity of saturated liquid

σ = surface tension of vapor - liquid interface

T_{Sat} = saturation temperature

ν_{fg} = specific volume difference at saturation

To obtain $\Delta T'_W$, set $q''_i = q''_{Convection}$ and solve for $\Delta T'_W$. Combining equation (2) and (6), we obtain:

$$h \Delta T'_W + h\, \Delta T_B = \left(\frac{h_{fg}\, k}{8\, \sigma T_{Sat}\, \nu_{fg}} \right) (\Delta T'_W)^2 \tag{7}$$

$$\Delta T'_W = \frac{1 + \sqrt{1 + 4\ \Gamma\, \Delta T_B}}{2\, \Gamma} \tag{8}$$

where,

$$\Gamma = \left(\frac{h_{fg}\, k}{8\, \sigma T_{Sat}\, \nu_{fg}} \right) \left(\frac{1}{h} \right)$$

In KSBOIL code, Γ is approximately given by $f(P)/h$ where:

$$f(P) = \left(\frac{1}{0.0102} e^{P/1437} \right)^2 = \left(\frac{h_{fg}\, k}{8\, \sigma T_{Sat}\, \nu_{fg}} \right) \tag{9}$$

Therefore:

$$\Delta T'_W\,(KSBOIL) = \frac{1 + \sqrt{1 + 4\, f(P) \dfrac{\Delta T_B}{h}}}{\dfrac{2\, f(P)}{h}} \tag{10}$$

The expression for $\Delta T'_W$ in equation (10) is now used in equation (5) to calculate q''_{Bi}. Then, equations (1) and (3) is solved for $q''_{Boiling}$. The mass evaporation rate $(\dot{m}_e)$ is calculated for every axial increment as:

$$\dot{m}_e = \frac{q''_{Boiling}}{h_{fg}} \tag{11}$$

2.2 Sensitivity Factor

In order to relate the variations in plant operating parameters to $\dot{m}_e$ variations, a variation factor, defined by the following equation, is used:

$$y = \frac{\dot{m}_e\,(variable)}{\dot{m}_e\,(nominal)} \tag{12}$$

The value of $\dot{m}_e\,(nominal)$ is determined by considering the values of all the operating parameters to be at their nominal or best estimate values. The value of $\dot{m}_e\,(variable)$ is based on values of the operating parameters including their deviations from nominal or best estimate values. The variation factor is considered to be affected by changes in the values of the operating parameters according to a relation of the form:

$$\frac{dy}{y} = S_1 \frac{dx_1}{x_1} + S_2 \frac{dx_2}{x_2} + S_3 \frac{dx_3}{x_3} + \ldots\ldots + S_n \frac{dx_n}{x_n} \tag{13}$$

The factor S_i represents the sensitivity factor associated with the i^{th} parameter. If all the plant operating parameters are held constant except for one, and the x_i is independent:

$$S_i = \frac{\partial y / y}{\partial x_i / x_i} = \frac{\partial (\ln y)}{\partial (\ln x_i)} \tag{14}$$

Thus the value of S_i can be interpreted as representing the percentage change in $\dot{m}_e$ resulting from a 1 percent change in x_i, all other parameters being held constant.

3. Results and Evaluation

3.1 $\dot{m}_e$ Comparison at Various Plant Operating Conditions

For the $\dot{m}_e$ comparison at various plant operating conditions, Kori Units 3&4 and Ulchin Unit 1 were selected as target plants. Those plants have been evaluated to have high AOA susceptibility based on the core surveillance data. The initial comparison of $\dot{m}_e$ values was done for Kori Units 3&4 using the design and measured core parameters such as RCS flow and inlet temperature. The results of $\dot{m}_e$ comparison are given in Table 1. From the Table 1, we believe that the measured flow and design inlet temperature are the most conservative combination of any others to assess AOA risk.

Based on the above result, the calculation of $\dot{m}_e$ through several operating cycle of Ulchin Unit 1 was completed as shown in Figure 2. It shows that $\dot{m}_e$ value is highly increased since cycle 10. It means that peaking factor was also increased due to the high burn-up Vantage 5H fuel loading. Thus the peaking factor, $F^N_{? H}$, is the one of the major parameters to affect the $\dot{m}_e$ value.

3.2 Sensitivity Study of Plant Operating Parameters

To determine the functional relation between $\dot{m}_e$ variation and plant operating parameters, $\dot{m}_e$ value was calculated for one variable at Kori Units 3&4 core condition. The results of $\dot{m}_e$ calculation as a function of power, inlet temperature and flow are given in Figures 3, 4 and 5, respectively. It shows that each parameter is linearly proportional to $\dot{m}_e$. The sensitivity of each parameter is determined by equation (14). The sensitivity factors are roughly 4.18 for core power, 13.52 for inlet temperature and -3.11 for RCS flow.

3.3 AOA Risk Assessment

Figure 6 provides us the typical guideline of AOA risk in terms of $\dot{m}_e$. It shows that AOA experienced oversea PWR plants have around 300(lbm/hr-ft^2) of $\dot{m}_e$. This is useful information to provide the guideline of AOA risk for Korean PWR plant. From this guideline, it is expected that Kori Units 3&4 and Ulchin Unit 1 plant have high AOA susceptibility. Since Vantage 5H fuel was loaded in those plants, the occurrence of AOA has frequently been observed in it based on the surveillance of core follow data. Therefore, $\dot{m}_e$ is acceptable to the best indicator of AOA risk in the case of Korean PWR plants as well.

Even though $\dot{m}_e$ and AOA are not currently safety evaluation requirements, there are significant impacts on the shutdown margin and F_Q surveillance factor. In order to prevent AOA related impacts in the reload core, the possibility of the occurrence of AOA must be reduced. It might be achieved substantially making the proper limitations in terms of peaking factor and plant operating parameters. Based on the sensitivity factor of each plant operating parameter, if reactor operating power is increased to 5%, the inlet temperature should be decreased to 1.6% or the RCS flow should be increased to 6.7% to prevent AOA risk.

4. Conclusion

Based on the evaluated results using KSBOIL code at various plant operating condition, it is concluded that mass evaporation rate, $\dot{m}_e$ must be considered to be as an indicator of AOA risk for Korean PWR plants. And, the possibility of AOA occurrence is significantly increased in domestic plants due to the loading of high burn-up fuel. For the conservatism of $\dot{m}_e$ calculation, the measured RCS flow and design inlet temperature should be used to assess AOA risk.

From the results of sensitivity study relative to the plant operating parameter, the sensitivity factors are roughly calculated to be 4.18 for core power, 13.52 for inlet temperature and -3.11 for RCS flow. Therefore, the plant operating parameters and peaking factors should be properly considered to minimize AOA risk in any changes of reactor core condition.

Acknowledgement

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References

1. KSBOIL User’s Manual, Westinghouse Inc., 1997.

2. J. G. Collier, “Convective Boiling and Condensation,” Third edition, McGraw Hill, 1996.
3. A. E. Bergles and W. M. Rohsenow, “The Determination of Forced Convection Surface Boiling Heat Transfer,” J. Heat Transfer, August 1964, page 365-372.
4. W. M. Rohsenow and J. P. Harnett, “Handbook of Heat Transfer,” McGraw Hill, 1973.

Table 1. Mass Evaporation Rate Calculation using Design and Measured Core Condition

Condition	Peak $F^{N}_{?\ H}$	Flow (gpm)	Tin (°F)	M-dot-e (lbm/hr-ft^2)
Kori Unit 3 Cycle 11	1.493	302100.0*	557.92*	357
		294139.0	557.92	386
		294139.0	557.12	380
		302100.0	557.12	349
Kori Unit 3 Cycle 12	1.467	302100.0	557.92	330
		294518.0	557.92	356
		294518.0	555.75	334
		302100.0	555.75	307
Kori Unit 4 Cycle 10	1.487	302100.0	557.92	351
		295063.0	557.92	376
		295063.0	556.43	362
		302100.0	556.43	336
Kori Unit 4 Cycle 11	1.493	302100.0	557.92	357
		294001.4	557.92	382
		294001.4	555.92	369
		302100.0	555.92	337

* Design Values

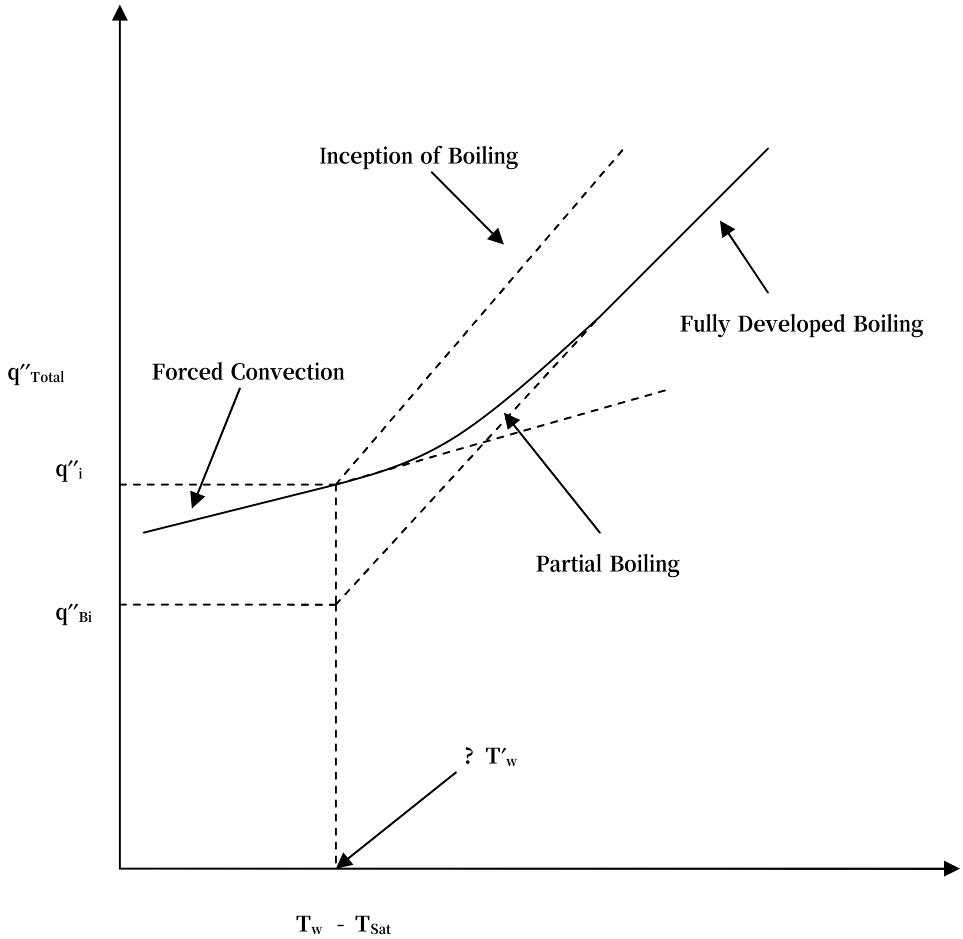

Figure 1. Bergles and Rohsenow Boiling Model

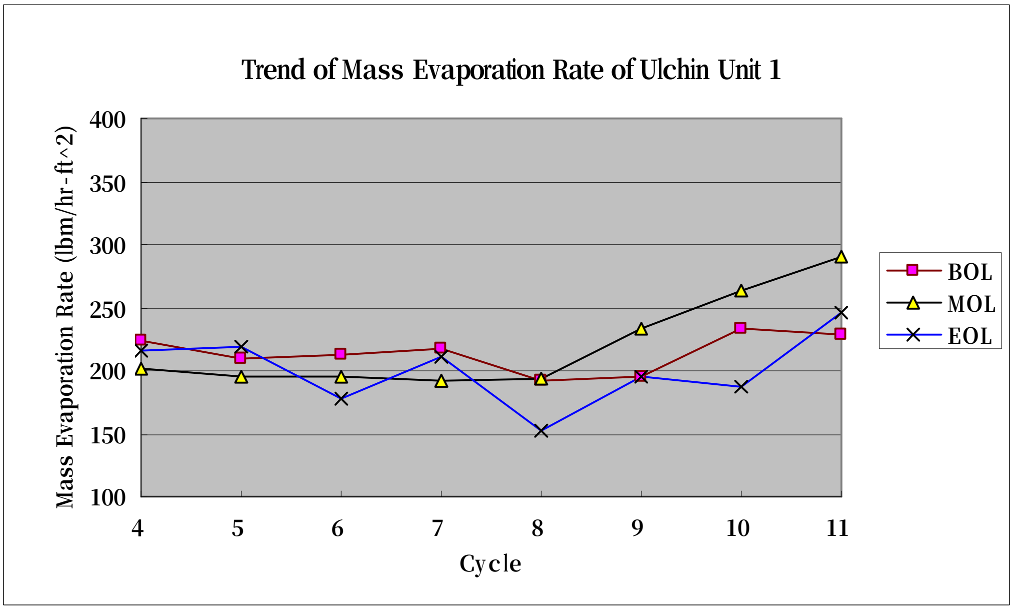

Figure 2. The trend of $\dot{M}_e$ variation for Ulchin Unit 1

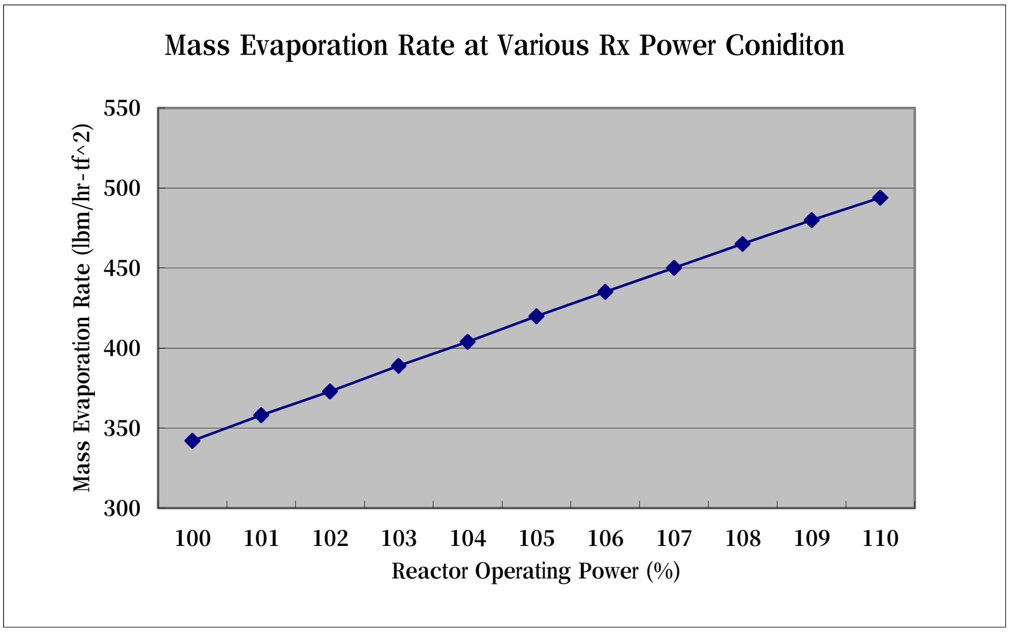

Figure 3. $\dot{M}_e$ at Various Rx Power Condition for Kori Units 3&4

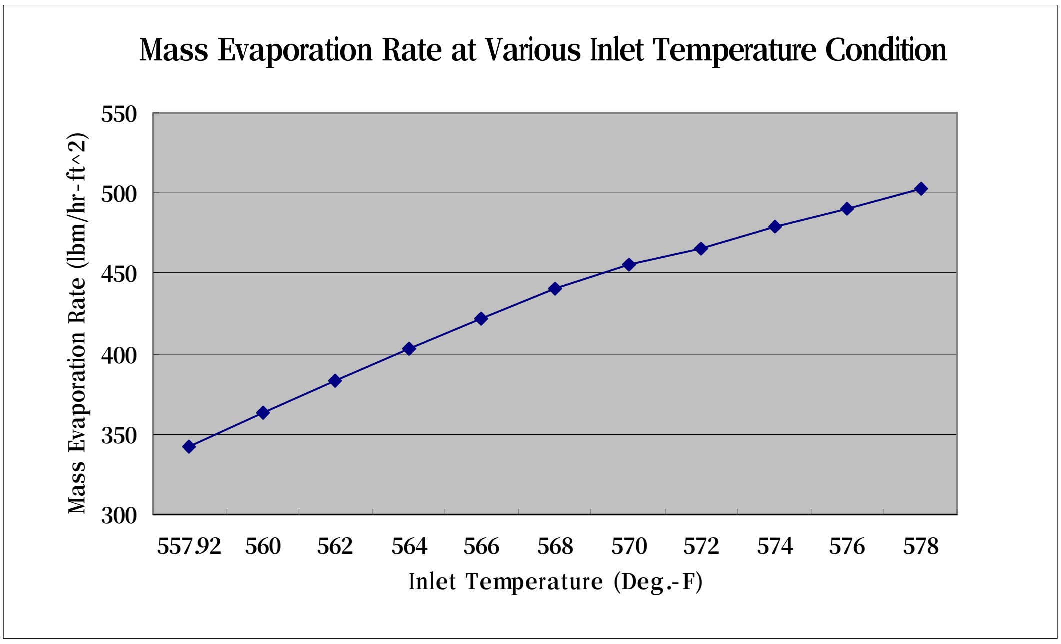

Figure 4. $\dot{M}_e$ at Various Inlet Temperature Condition for Kori Units 3&4

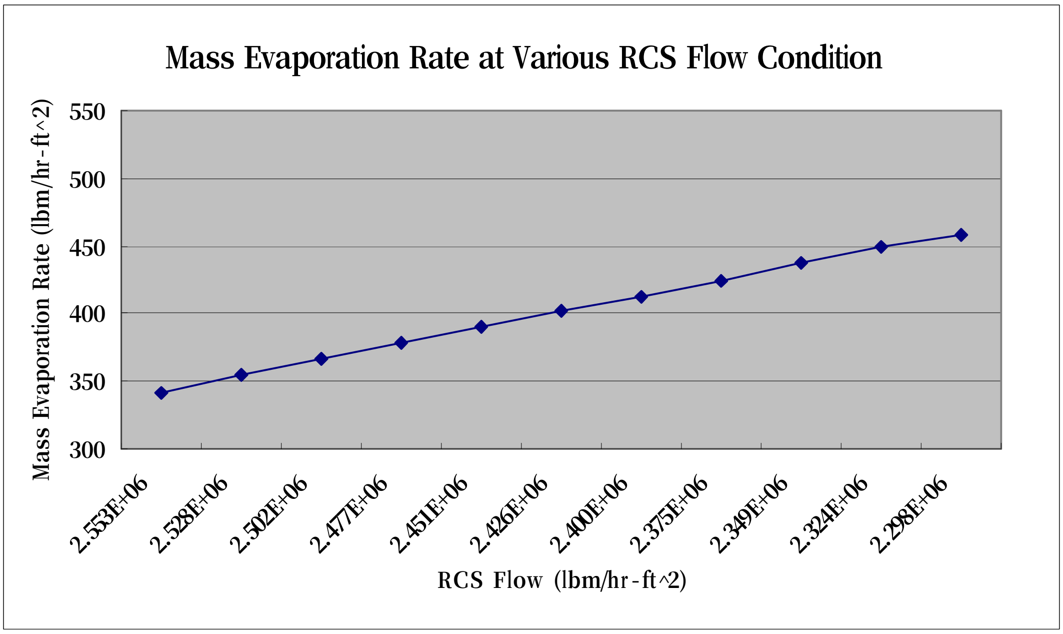

Figure 5. $\dot{M}_e$ at Various RCS Flow Condition for Kori Unit 3&4

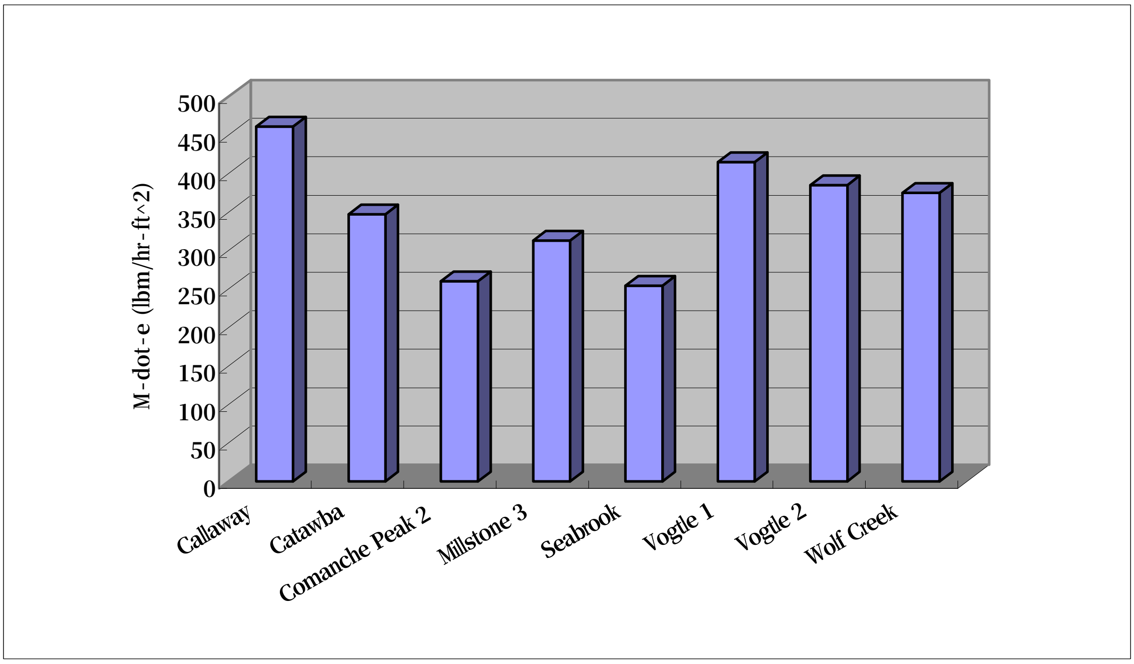

Figure 6. Comparison of $\dot{M}_e$ between AOA experienced oversea PWR plants