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A Study on Measuring Hot Leg Temperature with Core Exit Thermocouple in In-Core Instrumentation Guide Tube

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1. Introduction

The Optimized Power Reactor 1000 (OPR1000) is a Pressurized Water Reactor (PWR) with thermal power of 2,815MWt. The major components of the Reactor Coolant System (RCS) are one hot leg, two cold legs, one steam generator and two pumps on each loop (two parallel heat transfer loops exist), a pressurizer connected to the hot leg in one RCS loop with a surge line and a reactor vessel.

The hot leg temperature is measured by eight Resistance Temperature Detectors (RTDs) installed in two hot leg pipes. Among them, two RTDs are located in the upper region and another two are located in the lower region around the wall on each hot leg pipe.

The measured values from these eight RTDs are averaged to define the hot leg temperature of RCS. However, this method loses credibility as the temperature variations among the eight RTDs get wider during the plant lifetime due to thermal hydraulic phenomena such as thermal stratification from the reactor vessel to the hot leg pipes. It has been observed that this is attributed to a non-uniform temperature distribution in a cross section of the hot leg [1].

The thermal stratification is accelerated during the plant lifetime as fuel loading distribution in the reactor core follows Low Leakage Loading Pattern (L3P) which concentrates more power in the core center region. This helps to increase economic efficiency by reducing neutron leakages to the outside of the reactor core.

As the measured temperatures in the hot leg pipe with the RTDs are affected by the thermal hydraulic phenomena and this effect is unpredictable, this study aims to develop other methods of measuring the hot leg temperature to tackle this issue. The methods introduced in this study are using the temperatures measured by Core Exit Thermocouples (CETs).

2. Methods and Results

2.1 Analysis Method Description

Main causes of the thermal stratification from the reactor vessel to the hot leg pipe are as follows. First, the flow length from the reactor core exit to the RTDs located in the hot leg is not enough for the coolant to be fully mixed (Fig. 1). Second, the L3P of the fuel concentrates the thermal power at the center of the reactor core. This makes the temperature difference between the center and outer regions of the reactor core bigger at the core exit plane.

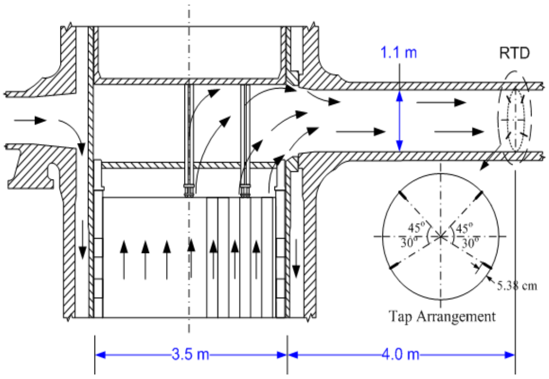

Fig. 1. Reactor coolant flow path from the reactor core exit area to the RTDs located in the hot leg.

The 45 CETs are installed at the end of In-Core Instrumentation (ICI) guide tube in the OPR1000 plant. Those are evenly distributed throughout the reactor core (Fig. 2).

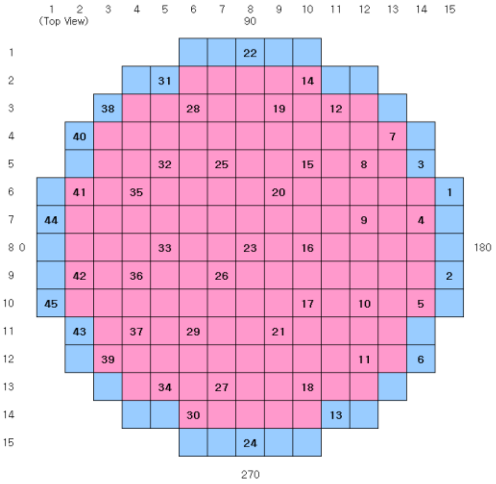

Fig. 2. CET locations in the reactor core of OPR1000

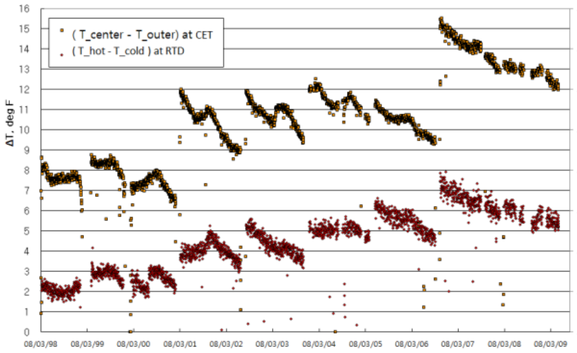

Fig. 3. Temperature differences measured by CETs at the center and outer regions and measured by RTDs at hot and cold legs (HUN 3, 1~9 cycles)

Fig. 3 shows the temperature differences measured by the CETs and RTDs with time. The data from CETs are based on temperature differences between the red and blue regions in Fig. 2, and the RTDs data are calculated by subtracting the cold leg temperature from the hot leg temperature. As Fig. 2 shows, there seems to be a strong correlation between the two data.

To measure the hot leg temperature as accurately as possible, two methods are introduced in this study using the CETs with some adjustments. One is to use the measured data obtained from the OPR1000 plants, and the other is to calculate the temperature differences between the coolant through the ICI guide tube and in the hot leg pipe analytically.

2.2 Experimental Method

The flow rates calculated by Heat Balance method (HB method) using the measured temperatures in the hot and cold leg pipes and Reactor Coolant Pump Differential Pressure method (RCP DP method) using the measured differential pressure are compared in Fig. 4. In the figure, the flow rates measured by the HB method tend to decrease with cycles, but the flow rates measured by the RCP DP method appear relatively constant.

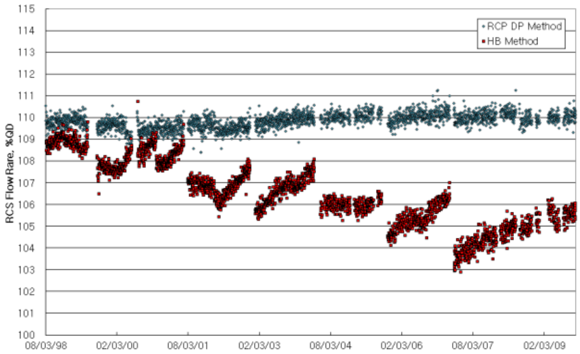

Fig. 4. RCS flow rates obtained from RCP DP and HB methods (HUN 3, 1~9 cycles)

The flow rates measured by the HB method have tendency to decrease during the plant lifetime. Hence, it seems reasonable to assume that the measured hot leg RTD temperature at the beginning of the 1st cycle is relatively closest to the real hot leg temperature. These data is used to estimate the adjustment factor (ΔT, defined as the differential between hot leg temperature and temperature measured by CETs). From the beginning of 1st cycle temperatures of RTDs and CETs for HUN 3 and 4, the ΔTs are calculated and summarized in table I.

Table I: The Result of Experimental Method

	T at RTD (˚F)	T at CET (˚F)	Δ T (˚F)
HUN 3	616.4	584.9	31.53
HUN 4	616.9	586.9	30.08

2.3 Analysis Method

The 45 CETs are installed inside the ICI guide tube in the OPR1000 plant. A small amount of flow enters into the inside of the ICI guide tube. This flow does not directly get to the surface of the fuel rod. This flow is heated up by convection and conduction through the ICI guide tube wall. The temperature differential between the hot leg and CET is defined as follows.

$$\Delta T = T_H - T_{\text{guide tube exit}}$$

In the above equation, T_H refers to the hot leg temperature (612.2˚F is the design value of the OPR1000 plant). And $T_{\text{guide tube exit}}$ indicates the coolant temperature inside the ICI guide tube at the exit, i.e, CET. To get the $T_{\text{guide tube exit}}$, heat transfer from outside of the ICI guide tube to the inside of the ICI guide tube is analyzed.

As a result, the temperature differential between the hot leg and the guide tube exit during normal operation, ΔT, is calculated at 30.81˚F.

3. Conclusions

In this study, new ways to estimate the hot leg temperature using the measured temperature at the CETs are introduced. The analyzed temperature differences(ΔT) between the hot leg and the CET are as follows.

1) ΔT (experimental method): 30.08 ~ 31.53˚F

2) ΔT (analysis method): 30.81˚F

For comparison, the flow rates are calculated by using those results, and those are included in Figs. 5 and 6.

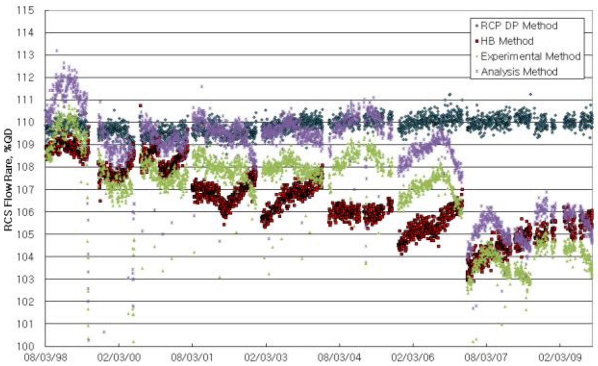

Fig. 5. RCS flow rates calculated by various methods (HUN 3)

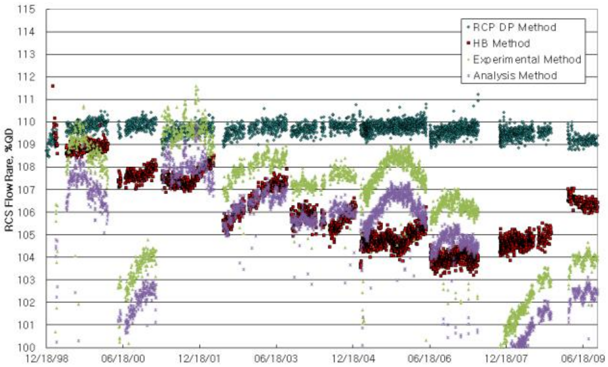

Fig. 6. RCS flow rates calculated by various methods (HUN 4)

Figs. 5 and 6 show the flow rate with time by various methods. At the earlier cycles in Fig 5, the experimental and the analysis methods generate more precise and coherent results than the HB method does. However, in some parts of Fig. 6, the flow rates by the experimental and analysis methods are significantly low. It means that those methods calculated the hot leg temperatures higher than actual one.

To solve the problem, it is considered that additional interpretation is necessary. For the sophisticated analysis, dividing CET distribution in center, middle and outer regions and applying the adjustment factors to each divided region are expected to improve an accuracy of the result. Furthermore, the deeper understanding on the behavior of the thermal stratification in the hot leg pipe will be helpful.

If the accuracy of the data increases and the effectiveness of the method is proven, measuring hot leg temperature (and flow rate) using the CET data could be used as the sub-calculating method in case of necessity.

REFERENCE

[1] H. C. Jang, An Analysis of Hot Leg Thermal Stratification Effect on Hot Leg Temperature Measurement for KSNP, Oct., 2002.