*Proceedings of the Korean Nclear Society Spring Meeting*
*Cheju, Korea, May* 1996

# Hot Leg Temperature Uncertainty due to Thermal Stratification

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## Abstract

For the Reactor Coolant System(RCS) flow rate measurement by the secondary calorimetric heat balance method, the coolant temperature of the hot leg is needed. Several Resistance Temperature Detectors(RTD) are installed in the hot leg to measure the temperature, but the average value of RTDs does not correctly represent the energy-averaged(bulk) temperature because of the thermal stratification phenomenon. Therefore some correction is introduced to predict the bulk temperature, but the correction inevitably contains uncertainty because the stratification is not defined well quantitatively yet. Therefore a large uncertainty for the correction has been used for the conservative estimation. But unrealistically large uncertainty causes degradation of the measurement method and yields difficulty to meet the acceptance criterion in start-up flow measurement test. In this paper, an analytical estimation is made on the correction and the related uncertainty using the measured hot leg velocity profile of System 80 reactor flow model test and the measured temperatures of YGN 3&4 and PVNGS 1&2 start-up tests. The results reveal that the magnitude of the correction uncertainty is much smaller than that used in the previous design. Therefore, the confidence on the flow rate measurement method can be improved and the difficulty in start-up flow measurement test can be lessened if the smaller correction uncertainty obtained through this estimation is applied.

## 1. Introduction

The uncertainty parameters related with the secondary calorimetric heat balance flow rate measurement method are the instrumentation uncertainties for the coolant temperatures and pressure, core power uncertainty, and the uncertainty for the hot leg temperature correction factor which come from the thermal stratification phenomenon. Among these uncertainty parameters, the uncertainties for the hot leg temperature correction and the core power are the major contributors on the overall uncertainty. Hot leg temperature stratification phenomenon means that the coolant temperatures in the upper region are higher than in the lower region, which has been observed in the previous experience.

There are four Core Protection Calculator(CPC) RTDs in each hot leg(Figure 1), i.e., eight

RTDs in two hot legs, to obtain the average hot leg temperature. But this average value does not represent the bulk temperature of the coolant passing through the hot leg pipe. Therefore some correction factor is introduced to compensate the difference between the average of RTDs and the bulk temperature. However the correction inevitably has uncertainty because it is impossible to get the exact value of the correction factor based on the existing information. Thus zero for the correction factor and a large value, which is believed to be definitely conservative, for the uncertainty of correction factor have been used in the previous design. In this paper an analytic and realistic estimation is made to obtain the best estimate and the limiting value for the correction factor using the measured velocity profile of the System 80 reactor flow model test[1] and the measured hot leg temperatures of YGN 3&4 and PVNGS 1&2[2,3] start-up flow measurement tests. The term "limiting value" means that an enveloping value which covers all the variation of the correction factor, i.e., the value of correction factor will not exceed the limiting value, so the limiting value can be used as the uncertainty of the correction factor.

## 2. Mathematical Analysis

### 2.1 RCS Flow Measurement and Hot Leg Temperature Correction

The basic equation for the determination of RCS flow rate by the heat balance method is as follows :

$$Q = \frac{v_c \dot{Q}}{h_H - h_C}$$

where, $Q$, $v_c$, $\dot{Q}$, $h_H$ and $h_C$ represent RCS volume flow rate, specific volume of cold coolant, core power, enthalpy of hot coolant and enthalpy of cold coolant, respectively. The uncertainty of the measured flow rate is calculated by combining the uncertainties of the individual parameters. Among the parameters, $h_H$ is related to the hot leg temperature stratification phenomenon. As mentioned before, the average of RTDs does not represent the bulk temperature, thus some correction is introduced as follows :

$$T^{bulk} = \frac{1}{8}\sum_{i=1}^{8} T_i + \Delta T_{HS} = T^{avg} + \Delta T_{HS} \qquad (1)$$

where $\Delta T_{HS}$ is the hot leg temperature correction factor. The uncertainty of $T^{bulk}$ can be obtained by the following equation[4] :

$$\sigma^2_{T^{bulk}} = \sum_{i=1}^{8}\left(\frac{\partial T^{bulk}}{\partial T_i}\right)^2 \sigma^2_{T_i} + \left(\frac{\partial T^{bulk}}{\partial \Delta T_{HS}}\right)^2 \sigma^2_{\Delta T_{HS}}$$

where $\sigma_{\Delta T_{HS}}$ represents the uncertainty of $\Delta T_{HS}$. For YGN 3&4 design, $\Delta T_{HS} = 0$ and $\sigma_{\Delta T_{HS}} = 0.5$°F were used. The values of $\Delta T_{HS}$ and $\sigma_{\Delta T_{HS}}$ affect the measured flow rate itself and its uncertainty respectively. The physical definition of the $T^{bulk}$ is as follows[5] :

$$T^{bulk} = \frac{\int \rho C_P T v \, dA}{\int \rho C_P v \, dA} \quad (2)$$

where $\rho, C_P, T, v$, and $A$ represent the density, specific heat, temperature, velocity, and cross-sectional area of the hot leg pipe, respectively. From Equation (1), $\Delta T_{HS}$ is expressed as follows :

$$\Delta T_{HS} = T^{bulk} - T^{avg} \quad (3)$$

In this paper, $\Delta T_{HS}$ is estimated by Equation (3) using the $T^{avg}$ which was obtained during the start-up test and the calculated $T^{bulk}$ per Equation (2). For the limiting $\Delta T_{HS}$, a combination which produces maximum $\Delta T_{HS}$ is chosen among the local $v$ and $T$ profiles and for the best estimate $\Delta T_{HS}$, the local profiles of $v$ and $T$ itself are used.

## 2.2 Velocity Profiles in the Hot Leg

Generally the velocity of the upper half region in the hot leg pipe is known to be greater than that of the lower half region. It is believed that this phenomenon comes from the unique geometrical arrangement of the reactor and pipings and has been observed in the previous plant flow model test. In the YGN 3&4 flow model test, the velocity distribution in the hot leg was not measured. Therefore, in this paper, the velocity distribution of Palo Verde flow model test[1] is used. Figure 2 represents the schematic of traverse port locations. The velocity distributions for 6 traverse angles were measured in the model test. Figures 3 through 5 show the measured and curve fitted(least square method) velocity profiles for traverse angles 15°-195°, 45°-225° and 75°-255°. Velocity profiles for traverse angles 165°-345°, 135°-315° and 105°-285° have the similar trend with those of 15°-195°, 45°-225° and 75°-255° due to the symmetry, but the slopes of 15°-195°, 45°-225° and 75°-255° were slightly steeper than those of 165°-345°, 135°-315° and 105°-285°, respectively. All these profiles show that the velocity of the upper region is greater than that of the lower region. Velocity profile for 15°-195°(VP15-195) has steeper slope than that of VP45-225, and VP45-225 has steeper slope than that of VP75-255. In calculating $T^{bulk}$ as defined in Equation (2), the use of steeper slope velocity profile produces a larger difference of $T^{bulk} - T^{avg}$ than the flatter slope profile. Therefore for conservatism, the velocity profiles of 15°-195°, 45°-225° and 75°-225° were used. The curve fitted equations as a function of radius $r/r_o$ are as follows :

$$15°\text{-}195° : \; v = -16.1639(r/r_o)^3 - 9.8985(r/r_o)^2 + 26.7919(r/r_o) + 36.7079 \quad (4)$$

$$45°\text{-}225° : \; v = -14.5971(r/r_o)^3 - 6.6856(r/r_o)^2 + 20.9971(r/r_o) + 37.5765 \quad (5)$$

$$75°\text{-}255° : \; v = -27.4180(r/r_o)^4 - 4.2414(r/r_o)^3 + 18.8326(r/r_o)^2 + 7.4115(r/r_o) + 36.8523 \quad (6)$$

In the above velocity distributions, $r/r_o$ should be negative if $90° < \theta < 270°$ ,i.e., downward direction from the pipe horizontal center line and positive if $270° < \theta < 360°$ or $0° < \theta < 90°$ ,i.e., upward direction. For the estimation of limiting $\Delta T_{HS}$, the VP15-195 is used for all θ because this produces the larger $\Delta T_{HS}$. For the best estimate $\Delta T_{HS}$, the regions are divided into 3-regions(Figure 6). For the region 1 the VP15-195 is used, for region 2 the VP45-225 is used and for region 3 the VP75-255 is used. With the above velocity profiles, 68% of total flow passes through the upper half of the pipe if the VP15-195 is applied for all θ for the limiting $\Delta T_{HS}$ calculation; 61% of total flow for the best estimate $\Delta T_{HS}$ calculation.

### 2.3 Temperature Distribution in the Hot Leg

The local coolant temperatures at core exit region are not uniformly distributed because heating rate is different depending on the coolant paths in the core region. When the coolant goes to downstream it gets mixed. In the hot leg pipe where the measurement is taken, the coolant temperatures at any point of the pipe cross-section get very close to each other but not exactly the same. Generally the temperature of the upper region is slightly higher than that of lower region. The corrected temperature of RTD channel C and D (see Figure 1 for channel location) showed higher values than those of channel A and B for all four hot leg pipes (two for each unit) of YGN 3&4.

To calculate $T^{bulk}$ as shown in Equation (2), the temperature, including density, specific heat and velocity, should be expressed as a function of location. The assumed temperature distribution for this calculation is that temperature is linearly dependent on the vertical height only. Of course this assumption is not exact but the trend mentioned above is consistent with the assumed function. And from the fact that the core exit temperature distribution shows large variance but in the hot leg the variance is very small, one can assume that the coolant is sufficiently mixed flowing from the core exit to the hot leg RTD location. As mentioned before, $\Delta T_{HS}$ is estimated for two cases. For the best estimate $\Delta T_{HS}$, all four RTD temperatures(for one hot leg) are used to produce the linear temperature function. For the limiting $\Delta T_{HS}$, the maximum and minimum temperatures are used to calculate the slope of the linear function because this produces the larger difference of $T^{bulk}-T^{avg}$. The fitted temperatures as a function of vertical height for the best estimate and limiting cases are as follows :

Best Estimate Case : $$T=\frac{T^{lower}h_U-T^{upper}h_L}{h_U-h_L}+\frac{T^{upper}-T^{lower}}{h_U-h_L}h \qquad (7)$$

*where,* $T^{upper}=\frac{1}{2}(T^C+T^D)$, $T^{lower}=\frac{1}{2}(T^A+T^B)$, $h=|r/r_0|\cos\theta$, $h_U=\cos 45^o$, $h_L=\cos 135^o$

Limiting Case : $$T=T^{avg}-\frac{T^{upper}-T^{lower}}{h_U-h_L}\frac{h_U+h_L}{2}+\frac{T^{upper}-T^{lower}}{h_U-h_L}h \qquad (8)$$

*where,* $T^{avg}=\frac{1}{4}(T^A+T^B+T^C+T^D)$, $T^{upper}=MAX(T^A,T^B,T^C,T^D)$, $T^{lower}=MIN(T^A,T^B,T^C,T^D)$

h is positive for the upward from the horizontal center line and negative for the downward, and this is automatically determined by the sign of $\cos\theta$. In the calculation of limiting $\Delta T_{HS}$, the average value of $T^{upper}$ and $T^{lower}$ should be retained as the original average value of 4 RTDs despite that the maximum and the minimum temperatures are used because we are estimating $T^{bulk}-T^{avg}$. So Equation (8) is a curve that moves in parallel with the slope made by maximum and minimum temperatures to have the same average value of 4 RTDs.

### 2.4 Density and Specific Heat in the Hot Leg

The density and specific heat in the hot leg are functions of temperature. In the hot leg pipe cross-section, the temperature variation is so small. So the density and specific heat can be assumed to change linearly with temperature. The fitted equations for density and specific heat as a function of temperature are as follows :

$\rho\,[lb/ft^3] = 101.4126 - 0.184058\,T[℃]$, $C_P\,[Btu/lb/°F] = -3.57099 + 0.0157151\,T[℃]$

$\rho\,[lb/ft^3] = 104.6848 - 0.102255\,T[°F]$, $C_P\,[Btu/lb/°F] = -3.85037 + 0.0087306\,T[°F]$

### 2.5 Calculation of $T^{bulk}$

The velocity profiles and temperature distribution are obtained as a function of radius $r/r_0$ and azimuthal angle θ in Sections 2.2 and 2.3. $T^{bulk}$ is calculated using Equation (2).

$$T^{bulk} = \frac{\int_A \rho C_P T v\, dA}{\int_A \rho C_P v\, dA} = \frac{\int_0^{\pi}\int_0^1 \rho C_P T v y dy d\theta}{\int_0^{\pi}\int_0^1 \rho C_P v y dy d\theta} \tag{9}$$

In the above equation y means $r/r_0$. For the calculation of the limiting $\Delta T_{HS}$, Equations (4) and (8) should be inserted into Equation (9). For $90° < \theta < 180°$, $r/r_0$ should be negative in velocity equation. Therefore,

$$T^{bulk} = \frac{\int_0^{\pi/2}\int_0^1 \rho C_P (8)\,(4)\, y dy d\theta + \int_{\pi/2}^{\pi}\int_{-1}^0 \rho C_P (8)\,(4)\,|y| dy d\theta}{\int_0^{\pi/2}\int_0^1 \rho C_P (4)\, y dy d\theta + \int_{\pi/2}^{\pi}\int_{-1}^0 \rho C_P (4)\,|y| dy d\theta}$$

For the best estimate $\Delta T_{HS}$, Equations (4),(5) and (6) are used for the velocity and Equation (7) is used for the temperature distribution. As shown in Figure 6, the different velocity profiles are applied depending on the azimuthal angle, so the integral should be divided into several regions as below :

$$\begin{aligned} T^{bulk} =& \Big[ \int_0^{\pi/6}\int_0^1 \rho C_P (7)\,(4)\, y dy d\theta + \int_{\pi/6}^{\pi/3}\int_0^1 \rho C_P (7)\,(5)\, y dy d\theta + \int_{\pi/3}^{\pi/2}\int_0^1 \rho C_P (7)\,(6)\, y dy d\theta \\ &+ \int_{\pi/2}^{2\pi/3}\int_{-1}^0 \rho C_P (7)\,(6)\,|y| dy d\theta + \int_{2\pi/3}^{5\pi/6}\int_{-1}^0 \rho C_P (7)\,(5)\,|y| dy d\theta + \int_{5\pi/6}^{\pi}\int_{-1}^0 \rho C_P (7)\,(4)\,|y| dy d\theta \Big] \\ &\Big/ \Big[ \int_0^{\pi/6}\int_0^1 \rho C_P (4)\, y dy d\theta + \int_{\pi/6}^{\pi/3}\int_0^1 \rho C_P (5)\, y dy d\theta + \int_{\pi/3}^{\pi/2}\int_0^1 \rho C_P (6)\, y dy d\theta \\ &+ \int_{\pi/2}^{2\pi/3}\int_{-1}^0 \rho C_P (6)\,|y| dy d\theta + \int_{2\pi/3}^{5\pi/6}\int_{-1}^0 \rho C_P (5)\,|y| dy d\theta + \int_{5\pi/6}^{\pi}\int_{-1}^0 \rho C_P (4)\,|y| dy d\theta \Big] \end{aligned}$$

## 3. Results and Discussion

The estimated results for the best estimate and the limiting cases are as follows :

| | YGN 3 | | YGN 4 | | PVNGS 1 | | PVNGS 2 | |
|---|---|---|---|---|---|---|---|---|
| | Hot Leg 1 | Hot Leg 2 | Hot Leg 1 | Hot Leg 2 | Hot Leg 2 | Hot Leg 2 | Hot Leg 2 | Hot Leg 2 |
| Limiting $\Delta T_{HS}$ (°F) | 0.106 | 0.081 | 0.115 | 0.094 | 0.183 | 0.257 | 0.074 | 0.100 |
| Best Estimate $\Delta T_{HS}$ (°F) | 0.022 | 0.011 | 0.027 | 0.018 | 0.021 | -0.017 | 0.007 | 0.002 |

The estimated results show that : 1) The best estimate value for the correction factor is nearly zero. This supports the ABB-CE's design model which uses zero for the correction factor. 2) The limiting value for the correction factor is much larger than the best estimate value. Thus it is believed that the limiting value has a sufficient conservatism when it is used as an uncertainty of the correction. 3) The limiting value is much smaller than the uncertainty of the correction factor used in the previous design, 0.5°F. Thus it is thought that the previous estimation was excessively conservative.

From the results mentioned above, it is judged that the limiting value can be used for the analysis of the flow measurement uncertainty.

## References

1. Test Report TR-ESE-401, "System 80 Open Core Flow Model Outlet Traverse Test", L.M. Russel, Dec. 23, 1980.
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3. Test Report 72PA-2RX59, "RCS Flow Measurement 100%", - PVNGS Integrated Test Results Package for Palo Verde Unit 2.
4. "Describing Uncertainties in Single-Sample Experiments", S.J. Kline and F.A. Mcclintock, J. of Mechanical Engineering, Jan., 1953.
5. "Heat Transfer", 5th. ed., J.P. Holman, McGRAW-HILL International Book Company, 1981.

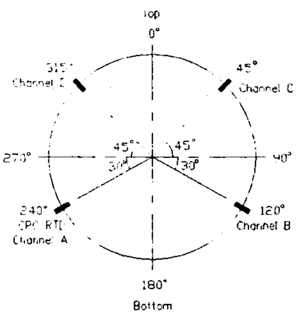


Figure 1 CPC RTD Channel Locations in the Hot Leg for YGN 3&4

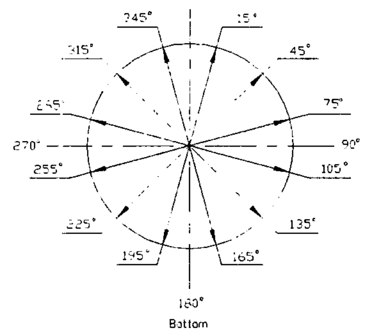


Figure 2 Schematic of Traverse Port Location

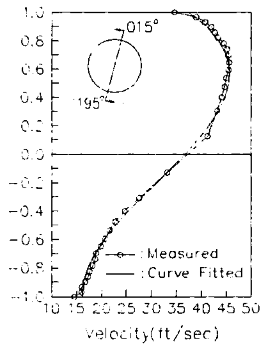


Figure 3 Velocity Profile for Traverse Angle 15° – 195°

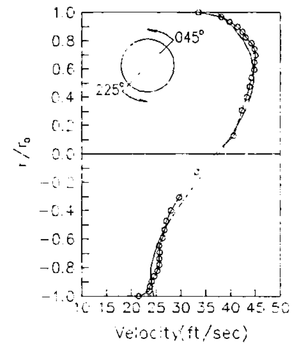


Figure 4 Velocity Profile for Traverse Angle 45° – 225°

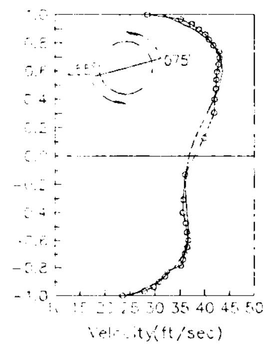


Figure 5 Velocity Profile for Traverse Angle 75° – 255°

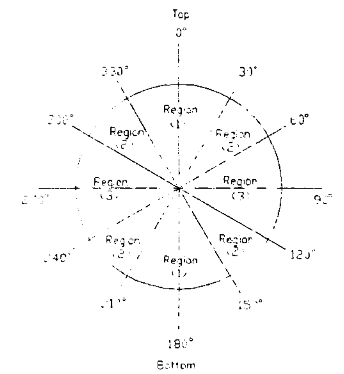


Figure 6 Divided Regions by the Pattern of the Velocity Profile