# HIGH RESOLUTION THERMAL MIXING AT WESTINGHOUSE ODEN LOOP

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## Abstract

In the evaluation of PWR fuel rod bundles for Critical Heat Flux (CHF) performance, an important parameter to consider is the Thermal Diffusion Coefficient (TDC), which is a measure of interchannel thermal mixing. This parameter, which can also be expressed as an inverse Peclet number, is one of many inputs to subchannel analysis codes such as VIPRE-W, THINC and TORC. TDC can be determined experimentally through single phase mixing tests which employ a 5x5 (or 6x6) simulated PWR rod bundle. The mixing test bundle is equipped with heated rods that have uniform axial power shape. Thermocouples are positioned in each subchannel at the End of Heated Length (EOHL). The bundle is operated over a wide range of flow, pressure and inlet temperature while the bundle power is adjusted to produce minimally subcooled conditions at EOHL. Traditionally, mixing tests were performed at Columbia University's Heat Transfer Research Facility (HTRF). In response to the permanent closure of HTRF in 2003, Westinghouse installed mixing test capability at its ODEN test facility in Västerås, Sweden. Newly developed software for TDC calculation that is interfaced with VIPRE-W now replaces the legacy FORTRAN codes which were scripted for HTRF and interfaced with TORC. A revised TDC optimization routine is applied to each mixing run by iteratively running VIPRE-W such that the code predicts a temperature (or enthalpy) distribution as close as possible to the subchannel measurements (after calibration and heat balance correction). The optimization is performed by minimizing the standard deviation of all flow-weighted enthalpy differences for a given mixing run. A series of mixing tests have confirmed that the ODEN loop produces accurate mixing data and that the new TDC software with VIPRE-W can efficiently repeat the TDC results produced by TORC.

**KEYWORDS**
TDC, Mixing, ODEN

## 1. INTRODUCTION

In a Pressurized Water Reactor (PWR), mixing vane spacer grids typically generate vortices in the flow field to enhance Critical Heat Flux (CHF) performance. The vortices also promote fuel rod convection by pushing cooler fluid from the subchannel center towards the hotter rod surfaces as discussed in [1]. Fuel designs exhibiting greater thermal mixing will exhibit a more uniform temperature distribution among the subchannels than designs with lower mixing ability. A subchannel analysis code, such as VIPRE-W or TORC [2], can be used to predict the fluid temperature field within the fuel assembly. VIPRE-W is the Westinghouse version of VIPRE-01 [3].

Mixing tests are performed to gather data that can be used to estimate the mixing ability of the spacer grids in a CHF test bundle. The data are post-processed to ultimately derive a Thermal Diffusion Coefficient (TDC), or an inverse Peclet number (1/Pe), for use in the subchannel analysis code. The TDC, or inverse Peclet number, is input to the mixing models contained in these subchannels codes for subsequent CHF analysis. A commonly used model for turbulent crossflow per unit length in the energy equation is:

$$w' = \beta * S * G_{avg} \tag{1}$$

where: $w'$ = turbulent crossflow per unit length
$\beta$ = mixing rate (dimensionless)
$S$ = gap distance between rods
$G_{avg}$ = average mass velocity in the adjacent channels

The mixing rate, β, is related to TDC and (1/Pe) as:

$$\beta = TDC = (1/Pe) * De/S \tag{2}$$

where: TDC = Thermal Diffusion Coefficient
Pe = Peclet Number
De = wetted subchannel hydraulic diameter

Turbulent mixing in two-phase flow is generally assumed to be the same as in single phase flow.

Westinghouse has been using the ODEN test facility for Critical Heat Flux (CHF) testing of simulated PWR fuel since 2010. The process for qualification of ODEN was discussed in [4]. The ODEN loop is located at the Västerås Thermal-Hydraulic Test Facility in Sweden. Westinghouse has added new mixing test capability to ODEN and devised a process for determination of TDC using the VIPRE-W subchannel code. This paper will present a description of the new capabilities at ODEN for running mixing tests and the methodology that can calculate TDC using VIPRE-W. Further, it will be shown that the TDC results based on VIPRE-W are equivalent to TDC results based on the baseline method used at the former Heat Transfer Research Facility (HTRF) with TORC.

## 2. MIXING TEST DESCRIPTION

### 2.1 Test Facility

As shown in Figure 1, ODEN consists of two independently operated sub-loops; one for the test section (right-hand side) where heat is added, the other for heat removal through a bank of heat exchangers (left-hand side). The sub-loops share a common suction to two pumps but each pump discharges to its respective sub-loop. In contrast, HTRF pumps shared a common discharge to both sub-loops. With a dedicated pump to the Test Section, the ODEN configuration reduces the risk of starving the Test Section of flow in the event of a rapid increase in two-phase pressure drop (such as during low flow/ low pressure operation).

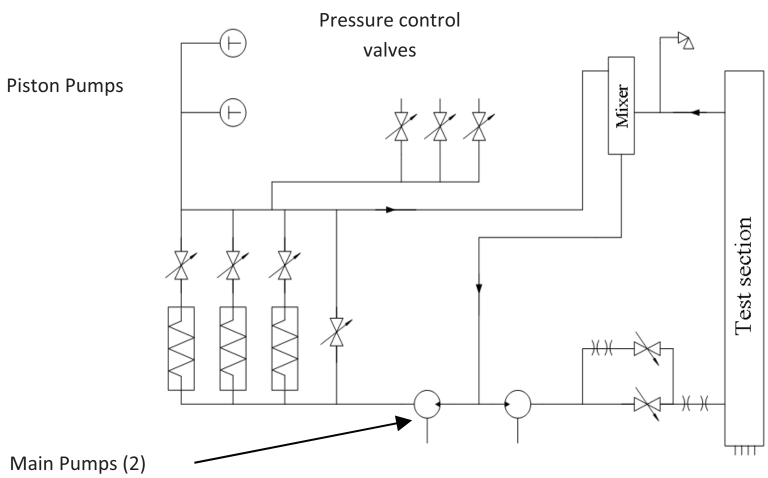



**Figure 1. Schematic of ODEN Loop**

Like HTRF, the ODEN pressure vessel is designed to accommodate full length test bundles containing 4x4, 5x5, 6x6, and various hex arrays of directly heated rods. Heated lengths can reach up to 4.3 m. ODEN is designed for 200 bar, 366 $^{0}$C, and flows to the test section of 0.7 to 22 kg/s. Power to the test section is based on a 400 max VDC (rectified AC) and 44 max kA electrical supply system. Depending on the actual rod bundle resistance, 15-16 MW is realizable at the test section when the heat exchangers are fully configured. HTRF had similar design range of pressure, temperature, and flow, though slightly lower power capability (12-14 MW).

Due to the use of directly heated rods (i.e., Joulean), water quality is carefully controlled with respect to conductivity level. In addition, oxygen content is restricted to reduce risk of corrosion. Since the mixing tests are run in single phase at minimally subcooled conditions, the power levels required for running a mixing test are considerably less than for CHF testing.

## 2.2 Loop Measurement and Control

All parameters which impact the safety-related data from testing are calibrated with traceability to Swedish national standards (SP Technical Research Institute of Sweden). These include inlet and outlet temperature, flow, pressure, and power (voltage, current). For extra quality assurance, each of these primary measurement channels has a calibrated redundant measurement channel. Measurement uncertainties are consistent with HTRF [6].

- Temperature – the bundle inlet and outlet temperatures are measured using several high precision resistance temperature detectors (RTD). The inlet temperature is regulated automatically (and manually) via control of flow through the heat exchangers.

- Flow – the bundle inlet flow is calculated based on pressure drop across dual inline orifices contained within special flow metering sections which were installed per ISO 5167 and ASME-MFE-14M-2001. One of two pipe diameters can be selected based on the range of flow being tested. An independent on-site check of the ODEN flow measurement system was performed by the SP Technical Research Institute and confirmed excellent agreement. Flow is regulated by control valves.

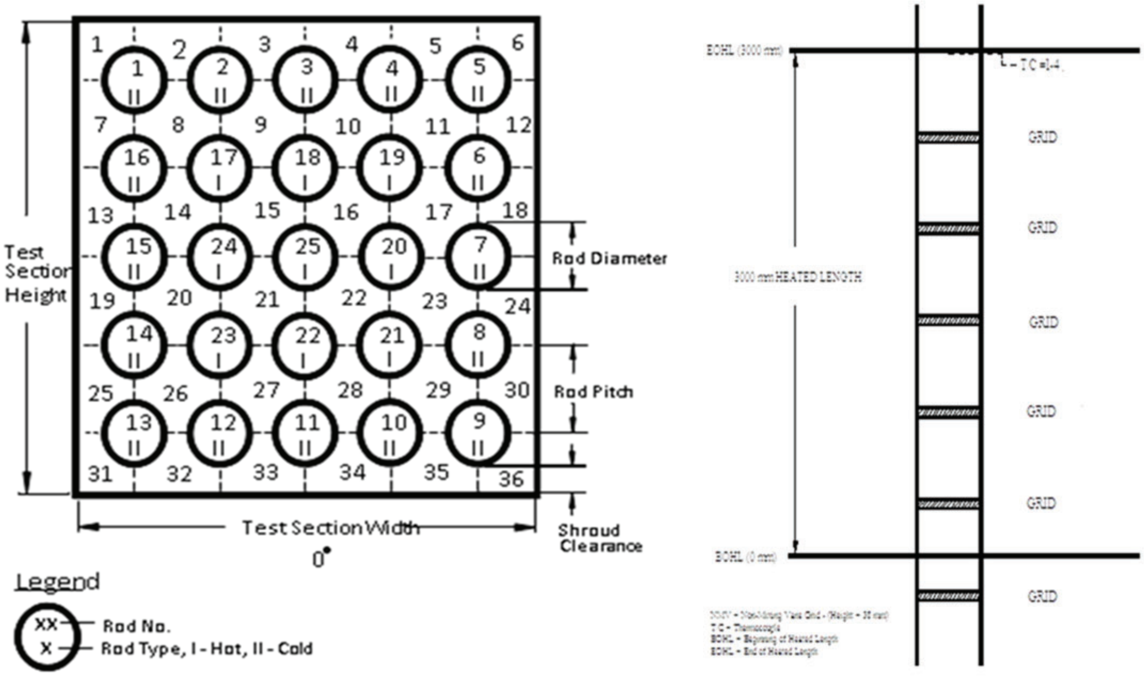
- Pressure – is measured with capacitance manometers. Pressure control is based on a bleed and feed approach, whereby pressure is reduced via water release and increased via make-up piston pumps. Pressure can be controlled either automatically or manually.

- Power – current is measured via Hall Effect sensors; voltage is measured across the positive and negative bus, and across the bundle heated length. Special rods equipped with voltage taps at the beginning and end of heated length enable a direct power measurement of the heated length. The true time varying power is calculated by computer.

## 2.3 Mixing Test Setup

Figures 2a and 2b, though based on a mixing test at HTRF, is a reasonable approximation of the radial and axial test geometry in the subject ODEN mixing tests (and later CHF tests). There were two mixing tests – one with an unheated guide tube, the other without a guide tube. Each employed a 5x5 array of electrically heated rods. The axial power shape was uniform and the radial distribution was non-uniform. The power applied to the outer rods near the unheated wall was approximately 15-20% reduced relative to the inner rods. Such a radial distribution is common in CHF testing to encourage CHF to occur away from the non-prototypical wall. The same setup was then used for subsequent CHF testing (not discussed in this paper). Each rod contained thermocouples at EOHL for detection of CHF.

Measurement of the radial temperature distribution is accomplished by thermocouples (TCs) inserted through the top pressure boundary. Axially, the tips of the TCs were positioned at the end of heated length (EOHL) and in the centers of each subchannel. The data acquisition system (DAS) consists of a system of multiple computers which handle the scan, monitor, display, and record functions for test section and loop measurements. The DAS can accommodate up to 288 heater rod TCs, 49 sub-channel TCs (for 6x6 test), plus 128 other channels. The scanning rate is 25 Hz. Data is recorded in 25 Hz and 5 Hz modes (averages of 25 Hz data). Transient and steady state data can be remotely accessed online.




**Figures 2a (Radial Geometry) and 2b (Axial Geometry) of Similar Mixing Test**

## 2.4. Test Procedure and Conditions

The mixing and CHF tests with uniform axial power distribution can be performed within the same experimental setup. All mixing data are taken in steady state, non-boiling (single phase) conditions. The mixing data consists of two types: isothermal calibration (power-off), and normal (power-on) mixing points. Isothermal calibration (power-off) mixing data is obtained to establish a calibration baseline over several conditions. The data are used for offline removal of possible biases in the raw subchannel temperatures measurements.

Normal (power-on) mixing data is obtained to provide the data used for calculation of TDC. One test consists of approximately 30 unique conditions (runs). The range of inlet temperature, flow, and pressure are shown in Table I. For each condition, power is pre-selected such that the hottest rod surface temperature is predicted to be 3-5°C below the saturation temperature (based on EOHL pressure). In operation, steady-state is established with fixed inlet temperature, pressure, flow, and power. Steady-state is defined as when the loop control parameters stay within their respective measurement uncertainties for at least 10 seconds. Each run (data point) is recorded in DAS based on a 10 second average of data scanned at 25 Hz. Data from the first few runs are checked and power adjusted to assure that the maximum subchannel temperature remains 3 – 5 °C below the saturation temperature (based on EOHL pressure).

Throughout the test, checks of single phase pressure drop and overall heat balances are regularly performed to assure loop integrity. The heat balance of the measured data was ~ 2 percent (also typical for CHF tests). This slight heat loss is later accounted for in the TDC analysis.

**Table I. Range of Mixing Conditions**

| Parameter | Nominal Range |
|---|---|
| Inlet Temperature (°C) | 190 – 280 |
| Pressure (bar) | 125 – 165 |
| Mass velocity (kg/m$^2$s) | 1300 – 4100 |
| Power (MW) | 1.0 – 4.6 |

## 3. CALCULATION OF THERMAL DIFFUSION COEFFICIENT (TDC)

### 3.1. Overview

This paper describes two methods for calculation of TDC as summarized in Table II. The baseline (historical) method has been used by Westinghouse with the TORC subchannel analysis code and HTRF mixing data. Calculation of TDC was performed via legacy FORTRAN routines optimized for interface with HTRF data files. A revised methodology has recently been developed which interfaces with VIPRE-W code and employs MATLAB-based scripts to rapidly perform the TDC calculations.

**Table II. TDC Calculation Methods**

| Method | Subchannel Code | Script language | Test facility files | Section in paper |
|---|---|---|---|---|
| Baseline | TORC | FORTRAN | HTRF | 3.4 |
| Revised | VIPRE-W | MATLAB | ODEN, HTRF | 3.5 |

The process for calculation of TDC is as follows (only step 4 is specific to the method used).

1) For each test, an isothermal calibration correction is determined for the raw subchannel temperature data at EOHL. The correction to a subchannel temperature is applied for each power-on run in a given test when the difference between the mean of all subchannel temperatures and the subchannel temperature exceeds twice the standard deviation on the mean of all subchannel temperatures in the isothermal calibration. Details are in Section 3.2.

2) The power-on conditions are applied in the subchannel code to predict subchannel temperatures and enthalpy at EOHL.

3) A heat balance correction is applied to the measured subchannel temperatures. This step slightly increases the average subchannel enthalpy at EOHL to match the subchannel code prediction (without heat loss). Details are in Section 3.3.

4) Within TORC (or VIPRE-W) for each power-on mixing run, TDC is iterated such that a global measure of the differences between the measured and predicted flow weighted enthalpy at EOHL in each channel is minimized.

5) The resulting iterated TDC for each power-on mixing run is collected and post-processed.

### 3.2. Isothermal correction

As stated earlier, the isothermal tests are used to determine if a correction is needed to the raw TC readings of any subchannel i, $T_{SC,i}$. The magnitude of the correction, $dT_{SC,i}$ , is based on the average of the TC subchannel readings for that calibration run, $T_{AVG}$, that is:

$$dT_{SC_i} = T_{AVG} - T_{SC_i} \tag{3}$$

The average $dT_{SCi}$ for all $N_{CAL}$ calibration runs is therefore,

$$dT_{SC\,i_{AVG}} = \frac{\sum_j^{N_{CAL}} dT_{SC\,i_j}}{N_{CAL}} \tag{4}$$

The standard deviation of all the temperature deviations for subchannel i, $dT_{SC,iSTD}$, when considered over all j calibration runs, Ncal, is then determined as:

$$dT_{SCi_{STD}} = \sqrt{\frac{\sum_j^{N_{CAL}} (dT_{SCi_j} - dT_{SCi_{AVG}})^2}{(N_{CAL}-1)}} \tag{5}$$

If $dT_{SC_i} > 2 * dT_{SCi_{STD}}$, then the corrected subchannel temperature is $T_{cal_i} = T_{SC_i} + dT_{SC_i}$ . Otherwise, $T_{cal_i} = T_{SC_i}$ .

### 3.3 Heat Balance Correction

In addition to the calibration of biased thermocouple measurements, a heat balance correction is applied (globally) to the power-on mixing subchannel temperature measurements. This is necessary to maintain the consistency between the measurements and the subchannel code predictions since the predictions (1) do not include heat loss to the environment, (2) do not include experimental uncertainties and, (3) consider a sub-channel average prediction rather than local, meaning the temperatures recorded in the center of the sub-channels do not identically correspond to the average temperature of the sub-channel. By applying a (global) heat balance correction to all sub-channels, the resulting total measured flow power agrees exactly with the code predicted values:

$$\mathrm{HM_i} = \gamma \mathrm{HM_i^{BHB}} \tag{6}$$

where:
$\mathrm{HM_i}$ = Measured enthalpy of sub-channel i, after calibration and heat balance correction
$\mathrm{HM_i^{BHB}}$ = Measured enthalpy of sub-channel i, after calibration but before heat balance
$\gamma$ = Global heat balance correction factor adjusted such as:

$$\sum_{k=1}^{N_{SUB}} \mathrm{W_i} * (\mathrm{HP_i} - \mathrm{HM_i}) = 0 \tag{7}$$

where:
$\mathrm{W_i}$ = Predicted exit mass flow of sub-channel i..
$\mathrm{HP_i}$ = VIPRE-W predicted enthalpy of sub-channel i.
$\mathrm{N_{SUB}}$ = Total number of considered sub-channels in test section .

The heat balance correction was approximately 2 percent in overall power, which is also consistent with the heat loss associated with other tests performed at HTRF and ODEN.

### 3.4. Baseline TDC Method (using TORC)

The mixing data from each mixing test were reduced with the special version of the TORC code, which interfaced with legacy FORTRAN-based scripts to iteratively evaluate the TDC. For each test point the TDC was iterated in the modified TORC code until the code determined subchannel exit conditions best matched to the measured exit conditions.

The optimization criterion is based on scanning exit coolant enthalpy differences $\Delta H_i$ (predicted minus measured) in subchannel i. These deviations are then weighted over the test section with the subchannel flow rate $W_i$. The optimization parameter $\Delta H$, is calculated from a combination of individual deviations and takes into account the deviations for all subchannels:

$$\Delta H = \sqrt{\sum_{i=1}^{Nsub} \frac{W_i}{W_{tot}} (HP_i - HM_i)^2} \tag{8}$$

Figure 3 shows an example [5] of the distribution of CFD and TORC-predicted subchannel temperatures versus the measured temperature (after isothermal and heat balance corrections) in a vaneless mixing test.

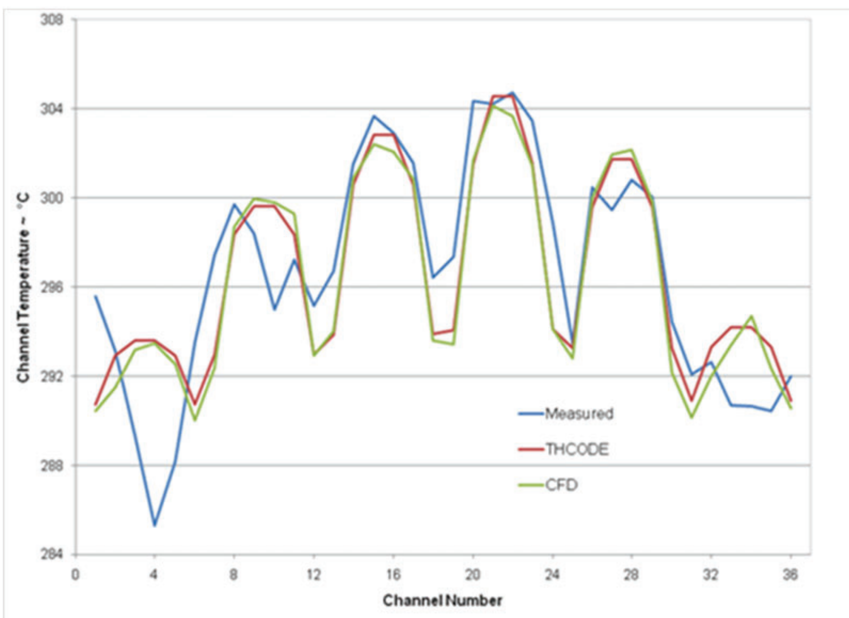



**Figure 3. Example of Sub-Channel Temperatures in a Mixing Test [5]**

The predictions are within reasonable agreement of the measurements for most sub-channels. A notable exception is sub-channel 4, located along the shroud wall. This local deviation is suspected to be an artifact of the test set-up.

### 3.5. Revised TDC Method (using VIPRE-W)

In the revised method, the optimized TDC for a given run is calculated by iteratively running VIPRE-W while varying TDC such that the code predicts a temperature (or enthalpy) distribution as close as possible to the measurements (after temperature correction (calibration) and heat balance correction). The optimization factor (ΔH) is proportional to the standard deviation of all flow-weighted enthalpy differences for a given run. All sub-channels are considered and the square of the measured enthalpy differences, weighted by the predicted sub-channel flowrates, are summed and dimensionalized to an enthalpy difference, as follows:

$$\Delta \mathrm{H} = \sqrt{\sum_{k=1}^{n} \frac{W_i^2}{W_{tot}^2} * (\mathrm{HP}_i - \mathrm{HM}_i)^2} \quad (9)$$

where:

$W_{tot}$ = Total mass flow of all sub-channels.

Rather than using legacy FORTRAN, the revised method employs a set of a set of MATLAB -based scripts which manage the VIPRE-W execution, read the inputs directly from the ODEN Data Acquisition System, then perform the iterative TDC optimization, and final post-processing. Options permit selection of various reference temperatures (TAVG) for the isothermal correction, as well as various optimization schemes.

## 4. COMPARISON OF METHODS

The methods for calculation of TDC using TORC and VIPRE-W are presented in this section. As can be readily seen in Figures 4 and 5, the results are equivalent. Figure 4 shows nearly identical differences in code predicted subchannel temperature versus the measured subchannel temperature. (It is noted that the measured temperature data has already been adjusted for calibration and heat balance). Since the mixing model selected for each subchannel code applies TDC uniformly amongst the channels, the result is a symmetric fluid temperature distribution. In reality, the vane pattern of the mixing vane grids produces a non-uniform temperature distribution. Thus, the differences between code and measurement subchannel temperature show non-uniformities (and thus non-zero values). However, each code demonstrates the same behaviour with respect to the data.

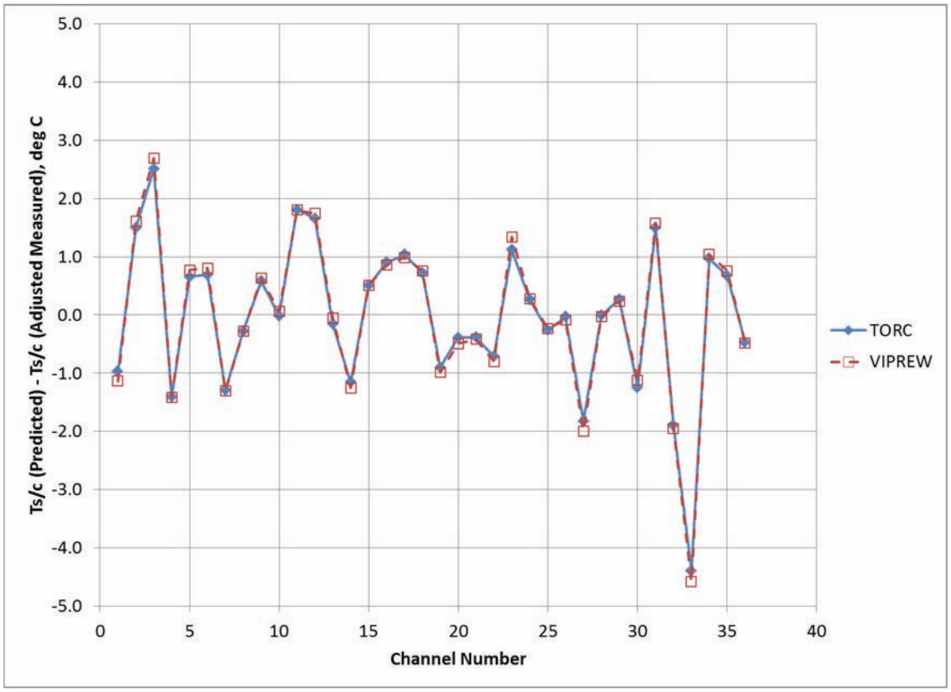



**Figure 4. Predicted Minus Measured Subchannel Temperature by Method**

Figure 5 further illustrates the equivalency of the two methods by plotting the code-to-code difference in TDC by condition for the two mixing test. The scatter is generally within 4% with average near zero.

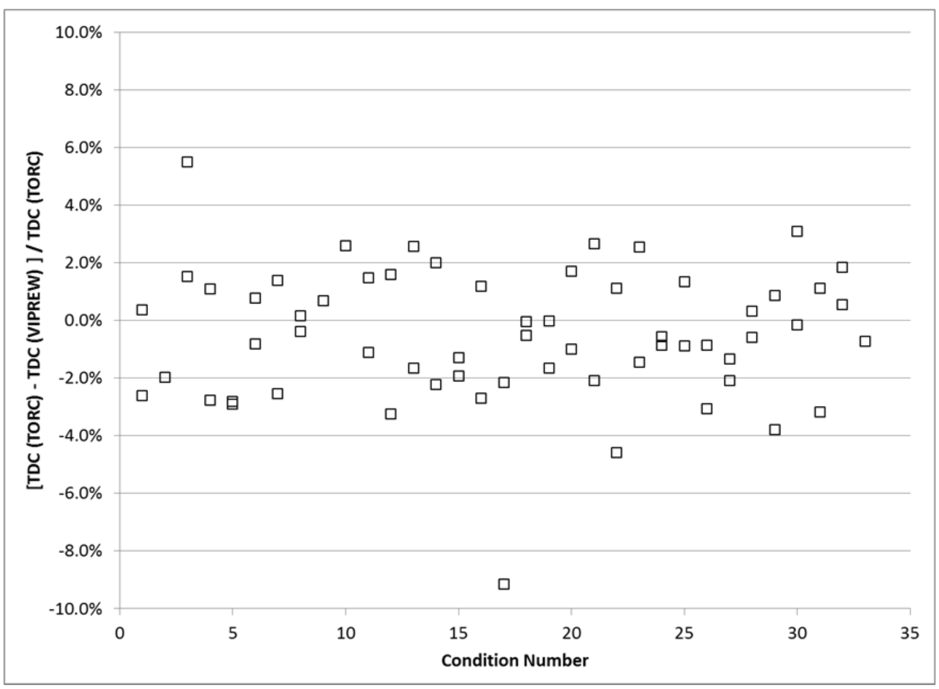



**Figure 5. Difference in TDC (Baseline vs. Revised Methods) by Condition**

## 5. CONCLUSIONS

The Westinghouse ODEN loop now has the capability for conducting thermal mixing tests for rod bundles. The loop has successfully demonstrated the ability to run such tests. Furthermore, a new set of software tools have been developed with MATLAB which can rapidly calculate the optimum TDC for each mixing run based on predictions of local fluid conditions generated by VIPRE-W. The TDC results based on this new method are equivalent to the TDC results produced using legacy FORTRAN routines in conjunction with the TORC subchannel code.

## NOMENCLATURE

| | |
|---|---|
| CHF | Critical Heat Flux |
| DAS | Data Acquisition System |
| HTRF | Heat Transfer Research Facility (Columbia, University, New York City) |
| PWR | Pressurized Water Reactor |
| TC | Thermocouple |
| TDC | Thermal Diffusion Coefficient |

## ACKNOWLEDGMENTS

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