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RCS Flow Measurement Using Elbow Tap Methodology for Yonggwang Unit 2

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Abstract

Recently, increases in hot leg temperature streaming were reported due to changes in the reactor core radial power distributions resulting from implementation of low leakage core loading patterns. Because of this effect, measured RCS flow appears to have decreased to the minimum measured flow required by the Technical Specifications. In order to resolve this problem, an alternative elbow tap flow measurement methodology has been developed and applied to Yonggwang Unit 2. The repeatability of the elbow tap flow measurements has been confirmed by comparing measured changes in elbow tap flows with changes predicted by the best estimate flow analysis. This new elbow tap flow measurement methodology has been found to be applicable to Yonggwang Unit 2. The proposed method can improve the RCS flow shortage by more than 1%.

1. INTRODUCTION

Reactor Coolant System (RCS) secondary plant calorimetric-based flow measurements at many pressurized water reactor (PWR) plants, including Yonggwang Unit 2, have been affected by increases in hot leg temperature streaming. The increases are related to changes in the reactor core radial power distributions resulting from implementation of low leakage core loading patterns (LLLPs). In some cases, measured flow appears to have decreased to, or below, the minimum measured flow required by the Technical Specifications. Such occurrences require licensee actions to either account for the apparent flow reduction in the plant safety analyses or to confirm by other means that flow has not decreased below the specified limit. In many cases, plants have relied on the repeatability of RCS elbow tap flow meters to demonstrate that RCS flow has not decreased. This alternative approach confirms RCS flow by a normalization process using elbow tap and calorimetric flow measurements obtained during the initial cycle or early cycles unaffected by changes in the core radial power distribution.

Technical Specifications usually require that RCS flow be measured once per fuel cycle and on a shift or daily basis throughout the cycle to demonstrate that the actual flow is greater than the minimum flow assumed for the safety analysis. The current RCS flow measurement method based on RCS temperatures and secondary calorimetric power measurements has inherent limitations imposed by LLLPs. The proposed alternative method that uses elbow tap flow measurements normalized to a measured baseline calorimetric flow minimizes these limitations.

2.0 RCS HOT LEG TEMPERATURE STREAMING

2.1 PHENOMENON

RCS hot leg temperature measurements are used in control and protection systems to ensure temperatures are within design limits, and in the RCS flow measurement procedure with secondary plant calorimetric power measurements to determine RCS flow. The uncertainty of hot leg temperature measurements can have a significant impact on PWR performance. A precise measurement of hot leg temperature is difficult due to the phenomenon called hot leg temperature streaming, i.e., large temperature gradients within the hot leg pipe resulting from incomplete mixing of the coolant leaving fuel assemblies at different temperatures. The magnitude of these hot leg temperature gradients where the temperatures are measured is a function of the core radial power distribution, mixing in the reactor vessel upper plenum, and mixing in the hot leg pipe.

Prior to application of LLLPs, the largest difference in fuel assembly exit temperatures at full power was typically less than 30°F (17°C), with the lowest temperatures measured at the exit of outer row fuel assemblies. Flow from a fuel assembly in the center of the core mixes with coolant from nearby fuel assemblies as it flows around control rod guide tubes and support columns to the hot leg nozzles. Flow from a fuel assembly on the outer row of the core, separated from the center region flows by the outer row of guide tubes, has little opportunity to mix with hotter flows before reaching the nozzles, so a significant temperature gradient exists at the hot leg nozzle.

Since hot leg flow is highly turbulent, additional mixing occurs in the hot leg pipe, and the maximum gradient where temperature is measured, 7 to 17 feet (2 to 5 meters) downstream from the reactor vessel nozzle, is less than the gradient at the nozzle. In

1968, the gradients measured on the pipe circumference at a 3-loop plant were as high as 7 to 10°F (4 to 6°C), so turbulent mixing in the pipe was not sufficient to eliminate the gradient introduced at the core exit.

Hot leg streaming measurements in 1968 and in subsequent measurements have shown that the highest temperatures are in the top half of the pipe, while the lowest temperatures are in the bottom half. This gradient was expected, since the colder water from the outer row of fuel assemblies is closest to the bottom half of the hot leg nozzle.

Figure 3-1 illustrates typical temperature gradients at the core exit and on the hot leg circumference at the point where the temperatures are measured. The core exit and hot leg temperature gradients change only slightly (typically less than 2 percent of coolant temperature rise (ΔT) across the core) as the radial power distribution changes during a fuel cycle.

2.2 HOT LEG STREAMING IMPACT ON RCS FLOW MEASUREMENTS

Before 1988, reports of hot leg temperature measurement problems were unusual, and no significant changes in streaming gradients were indicated. In 1988, the first significant indication of a streaming change occurred at a 4-loop plant, followed by similar occurrences in 1989 and 1990 at three more 4-loop plants. In all four cases, the measured coolant ΔT had increased from that measured in previous fuel cycles by as much as 3 percent. A ΔT increase of 3 percent implied that RCS flow had apparently decreased by 3 percent.

In 1990, both units at one plant site reported that calorimetric flows appeared to be below the Technical Specification requirement. Measurements from the elbow taps confirmed that RCS flow was adequate. The Nuclear Regulatory Commission (NRC) was advised of the apparent low calorimetric flow indication and the elbow tap flows, and concurred with the licensee's conclusion that flow was adequate for safe full power operation for the remainder of the cycle.

Many 3-loop and 4-loop plants reported apparent flow reductions after implementing LLLP. In all cases, however, elbow tap flows confirmed that the actual flow had not changed. It was also noted that core exit temperature gradients had increased, approaching 60°F (33°C), with lower temperatures being measured at the edge of the core. It was concluded that the increase in the core exit temperature gradient increased the hot leg streaming gradient, resulting in measured hot leg temperature being higher than the actual temperature. Many plants have applied the alternate elbow tap flow measurement procedure to avoid the impact of LLLP on the RCS flow measurement.

3.0 ELBOW TAP FLOW MEASUREMENT APPLICATION

The elbow tap flow measurement procedure relies on elbow tap Δp repeatability for accurate RCS flow verification. The comparison of elbow tap measurements from one cycle to the next provides an accurate indication of flow changes. When normalized to a baseline calorimetric flow measurement, elbow tap Δps define an accurate flow for future cycles. The elbow tap flow measurement procedure is described in the following paragraphs.

3.1 BASELINE CALORIMETRIC FLOW

Calorimetric flow measurements obtained during early fuel cycles before application of LLLP are compared to evaluate their accuracy and consistency for use in defining RCS baseline calorimetric flow (BCF). Calorimetric flows from these cycles are expected to be consistent with each other and with best estimate flow predictions.

One cycle (normally Cycle 1) is defined as the baseline cycle if the measured calorimetric flow meets the recommendations defined below, and if the elbow tap Δps were measured during the cycle. If Cycle 1 cannot be the baseline cycle, another early cycle with an acceptable calorimetric flow measurement and with elbow tap Δp measurements is defined as the baseline cycle.

The calorimetric flows from additional early cycles that meet the recommendations are also considered in the evaluation. These flows are corrected for known hydraulics differences so that the flows are hydraulically consistent with the baseline cycle hydraulics. The number of cycles used in the evaluation is limited to three, since including additional cycles provides minimal benefit in measurement accuracy or uncertainty, potentially increases the hydraulics uncertainty, and possibly introduces an LLLP bias.

Elbow tap flow measurement accuracy depends on defining an accurate BCF. The BCF is most accurate if the measured calorimetric flows used to define BCF meet all of the recommendations listed below. Recommendation (b) is mandatory. If the flows do not meet all of the other recommendations, an alternative methodology that best meets these recommendations shall be defined, justified and applied.

Recommendations for Calorimetric Flows used to Define BCF

a. The flow must be measured at or above 90% power at the beginning of the fuel cycle to minimize the calorimetric measurement uncertainty.

b. One cycle must have concurrent calorimetric flow and elbow tap Δp measurements.

c. To minimize the uncertainty in the hydraulics correction, the number of tubes plugged in the steam generators shall not exceed an average of 5%.

d. After correcting the calorimetric flows for known hydraulics differences from the baseline cycle, the early cycle calorimetric flows used to define BCF shall be within a 1% band, and shall be within 2% of the baseline cycle BEF.

The BCF is defined by comparing the average of up to three calorimetric flows with the individual calorimetric flows and with the BEF, and selecting a calorimetric flow that conservatively meets all of the recommendations defined above. The BCF is expected to be consistent with the best estimate flow(BEF).

The accuracy of the BCF is based on plant specific instrumentation uncertainties that existed when the calorimetric flow measurements used to define BCF were performed. An uncertainty allowance is included in the calorimetric flow measurement uncertainty to account for a hot leg temperature streaming error in averaging the streaming gradient existing in the cycle when the BCF was measured. Although LLLP introduces temperature streaming gradients and hot leg temperature biases that are much larger than those existing in the early cycles, the biases are more conservative, resulting in a lower measured flow, so a larger, LLLP-induced streaming uncertainty is not applied.

3.2 BASELINE ELBOW TAP DP

Elbow tap Δps obtained at 90 to 100 percent power in the cycle defined as the baseline calorimetric flow cycle define a baseline elbow tap flow coefficient, used in connection with the baseline calorimetric flow and a future cycle elbow tap flow coefficient to define a future cycle flow.

The baseline elbow tap flow coefficient (B) is defined by equation 1:

$$B = \Delta p_{\mathbf{B}} * v_{\mathbf{B}} \qquad \text{(Eq. 1)}$$

Where:

B = baseline elbow tap total flow coefficient (inches H_2O * ft^3/lb),

$\Delta p_{\mathbf{B}}$ = baseline average elbow tap Δp (inches H_2O),

$v_{\mathbf{B}}$ = average cold leg specific volume (ft^3/lb).

The baseline elbow tap flow coefficient, based on the average Δp of all elbow taps, defines total flow to be consistent with the total baseline calorimetric flow. Analyses of elbow tap Δp data at several plants has shown that the difference between total flow based on the average elbow tap Δp and total flow based on individual elbow tap transmitter Δps or loop average elbow tap Δps is negligible. The repeatability of the total flow measurement is improved when all elbow tap Δp measurements are used.

3.3 Flow Verification for Future Cycles

Elbow tap Δps obtained at the beginning of a future cycle define the change from the baseline flow. The average of all elbow tap Δps measured at 90 to 100 percent power defines the future cycle elbow tap flow coefficient (K), based on equation 2:

$K = \Delta p_F * v_F$ (Eq. 2)

Where:

K = future cycle elbow tap total flow coefficient (inches $H_2O * ft^3/lb$),

Δp_F = average future cycle elbow tap Δp (inches H_2O),

v_F = average cold leg specific volume (ft^3/lb).

The change in flow from the baseline cycle to the future cycle is defined by the elbow tap flow ratio (R), based on equation 3:

$R = (K / B)^{½}$ (Eq. 3)

where

R = ratio of future cycle flow to baseline flow.

The future cycle flow is determined by multiplying the baseline calorimetric flow by the elbow tap flow ratio (R), per equation 4:

$FCF = R * BCF$ (Eq. 4)

where

FCF = total future cycle flow, gpm,

BCF = total baseline calorimetric flow, gpm.

3.4 BEST ESTIMATE FLOW CONFIRMATION

A future cycle flow defined by elbow taps is confirmed by comparing the elbow tap flow ratio (R) with an estimated flow ratio (R'), based on the best estimate flow analysis (Section 5) of known RCS hydraulics changes such as steam generator tube plugging or fuel design changes.

The estimated flow ratio is defined by equation 5:

$R' = FEF / BEF$ (Eq. 5)

where

FEF = future cycle estimated flow, the estimated RCS flow, based on actual RCS hydraulics changes,

BEF = best estimate flow; estimated initial (baseline) cycle RCS flow, based on hydraulics analyses.

An acceptance criterion is applied to the comparison of R and R’:

If $R \leq (1.004 * R')$, the elbow tap flow ratio R is used to calculate the future cycle RCS total flow using Equation 4.

If $R > (1.004 * R')$, the quantity $(1.004 * R')$ is used to define the future cycle RCS total flow, modifying Equation 4 to equation 6 as indicated below.

$$FCF = 1.004 * R' * BCF \quad \text{(Eq. 6)}$$

The multiplier (1.004) applied to R' is an allowance for the elbow tap flow measurement repeatability. Since the elbow tap flow measurement uncertainty includes this repeatability allowance, the measured flow ratio (R) can be 0.4 percent higher than the estimated flow ratio (R’) and still define a conservative flow. Application of this acceptance criterion results in definition of a conservative future cycle flow, confirmed by both the elbow tap measurements and the best estimate hydraulics analysis.

4.0 EVALUATION OF YONGGWANG RCS FLOW PERFORMANCE

4.1 INTRODUCTION

RCS elbow tap flow and calorimetric flow measurements from Yonggwang (YGN) Unit 2 were evaluated and compared with best estimate flow predictions to evaluate the RCS flow performance. Elbow tap flow measurements most accurately define the actual changes in flow from cycle to cycle, and are expected to compare well with the changes predicted by the best estimate flow analysis.

Calorimetric flow measurements from each unit were used to define the baseline calorimetric flow. Changes in calorimetric flows were compared with changes in best estimate flow predictions and measured elbow tap flows to determine the magnitude of the changes that were not due to hydraulics changes. The evaluation included calculation of hot leg temperature streaming biases in later fuel cycles, expected to be the major cause of non-hydraulics-related flow changes.

The results of the YGN flow measurement evaluation are described in the following sections.

4.2 BEST ESTIMATE FLOW PREDICTIONS

Best estimate flows (BEFs) at full power were calculated for YGN 2, based on zero steam generator tube plugging, for the various fuel designs used at these plants. An additional BEF at zero power at YGN 2 was calculated to confirm the change in BEF for these plants as reactor power is increased from zero to 100%. The BEFs are listed in Table 4-1 below.

Table 4-1 Best Estimate Flows For Each Fuel Design –Gallons per minute

Plant	OFA, HFP	OFA, HZP	JDFA	V5H
YGN 2	307,139	309,737	309,878	305,281

BEFs for each cycle were determined by adjusting the BEFs in Table 4-1 for the hydraulics changes described below.

Reactor coolant pump performance was found to be reduced by a phenomenon called impeller smoothing, where the surface of a new impeller becomes smoother as surface roughness is reduced by wear, or as corrosion products collect on the impeller surface. Impeller smoothing is assumed to reduce RCS flow by 0.6% after Cycle 1 at YGN 2.

Steam generator tube plugging (SGTP) impacts the RCS flow by approximately 1% flow per 5% increase in SGTP. According to the tube plugging data applied in Reference 3, SGTP at YGN 2 has been minimal, and the impact on RCS flow was estimated to be –0.1% flow after Cycle 6.

BEFs normalized to the baseline cycle BEF (defined as 100% flow) are plotted on Figure 4-1.

4.3 BASELINE CALORIMETRIC FLOW

Calorimetric flow measurements obtained during early fuel cycles before application of LLLP are compared to evaluate their accuracy and consistency for use in defining RCS baseline calorimetric flow (BCF), applying the procedure defined in Section 3.1. Calorimetric flows from the early cycles are expected to be consistent with each other and with best estimate flow predictions. The results of the evaluation are presented in the following paragraphs.

Baseline Calorimetric Flow

YGN 2 measured calorimetric flows are listed in Table 4-2, along with the reactor power when the measurement was performed. Calorimetric flows listed in Table 4-2 are corrected for the lower power level, using – 1.0% flow from zero to 100% power.

The Cycle 1 calorimetric flow is somewhat lower than the BEF, while the Cycle 2 calorimetric flow is much higher than the flows for both Cycle 1 and Cycle 3. Since the Cycle 1 BEF (307,139 gpm) is about 2% above the Cycle 1 calorimetric flow, it was concluded that the average of the flows for Cycles 1, 2 and 3 would define a more reasonable, but still conservative baseline flow. This baseline flow **(304,533 gpm)** is about 0.8% less than the BEF. The YGN 2 calorimetric flows, normalized to the baseline flow (defined as 100% flow), are plotted on Figure 4-1.

4.4 ELBOW TAP FLOW MEASUREMENT EVALUATION

Elbow Tap Flows

Figure 4-2 plots the loop average elbow tap flow history for Cycles 1-7 and 12, normalized to the Cycle 1 measurement. The loop average measurements appear to track together.

Individual elbow tap Δp measurements were evaluated for repeatability. Figures 4-3 through 4-5 show the transmitter measurements for Loops 1 through 3 respectively. Loop 1 transmitters tracked very well with respect to each other. Cycle 6 data showed a small decrease in flow, but within the transmitter measurement repeatability. Loops 2 and 3 transmitters also tracked well. All of these measurements are considered to be well within the repeatability of the transmitters. Therefore, the Cycle 1 elbow tap measurements, in inches of water and adjusted for 100% power, are used as the baseline elbow tap Δp.

Table 4-2 Yonggwang Unit 2 Calorimetric Flows

Cycle	Power %	Measured gpm	Corrected gpm	% of Baseline %
1	100	301,085	**301,085**	98.9
2	100	310,819	310,819	102.1
3	99	301,724	301,694	99.1
4	74	323,055	322,225	105.8

5	73	300,366	299,552	98.4
6	74	297,164	296,377	97.3
7	75	297,918	297,185	97.6
8	100	297,971	297,971	97.8
9	100	295,586	295,586	97.1
10	100	296,081	296,081	97.2
11	100	306,131	306,131	100.5
12	100	301,874	301,874	99.1
Baseline	**100**		**304,533**	

4.5 RCS FLOW COMPARISONS

RCS Flows

Figure 4-1 compares measured calorimetric and elbow tap flow with BEF. The three flows are normalized to 100% flow in baseline Cycle 1. BEF and elbow tap flows are in good agreement for Cycles 1-5. The Cycle 6-7 elbow tap flows are below the BEF. This flow difference is apparently not entirely due to an optimistic flow resistance for JDFA fuel, loaded in Cycles 4-6. The difference could be due to a combination of non-repeatability of the elbow tap flows and an optimistic estimate of the fuel flow resistance. The elbow tap flow measurement in Cycle 12 (full core of V5H fuel) continues to show that the measured elbow tap flow is below the BEF. The Cycle 12 elbow tap flow is assumed to be correct and appropriate for flow verification purposes.

Calorimetric flows in Cycles 2, 4, 11 and 12 are unusually high and inconsistent with the other calorimetric flows and the trends defined by elbow taps and the BEF. Calorimetric flows in Cycles 5-10 appear to be consistent with the temperature bias theory, indicating a flow bias of more than 2% in most of these cycles. A review of the Cycle 11-12 calorimetric measurements may help to resolve the differences.

5.0 SUMMARY AND CONCLUSIONS

The alternative elbow tap flow measurement procedure has been found to be applicable to Yonggwang 2. The repeatability of the elbow tap flow measurements has been confirmed by comparing measured changes in elbow tap flows with changes predicted by the best estimate flow analysis. The evaluation of plant operating data has defined sufficiently accurate baseline parameters for both the elbow tap and calorimetric flow measurements.

The baseline calorimetric flow for Yonggwang 2, based on calorimetric flow measurements in Cycles 1, 2 and 3 is **304,533 gpm,** which is 99.2% of the Cycle 1 BEF of **307,139 gpm**. Part of this difference from the BEF may be due to a LLLP-biased calorimetric flow in Cycle 3. The calorimetric flows for Cycles 5-7, corrected for hydraulics changes, are as much as 1.5% lower than the elbow tap flow measurement, most likely due to LLLP. As shown on Figure 4-1, flow changes measured by the elbow taps are reasonably consistent with, or are conservatively lower than the predicted flow changes.

If the licensee apply that alternative elbow tap flow measurement methodology instead of secondary plant calorimetric-based flow measurement methodology, they can get more than 1% of RCS indicated flow which can meet Technical Specification requirement easily.

References

[1] “Yonggwang Unit 1&2 NSSS Parameters for SEE Input”, 12/01/00

[2] “SG Tube Plugging Status at Yonggwang 1&2 Units”, 7/14/99

[3] “RCS Flow Measurement Using Elbow Tap Methodology Licensing Submittal for South Texas Project Units 1&2”, 7/97(Non-Proprietary)

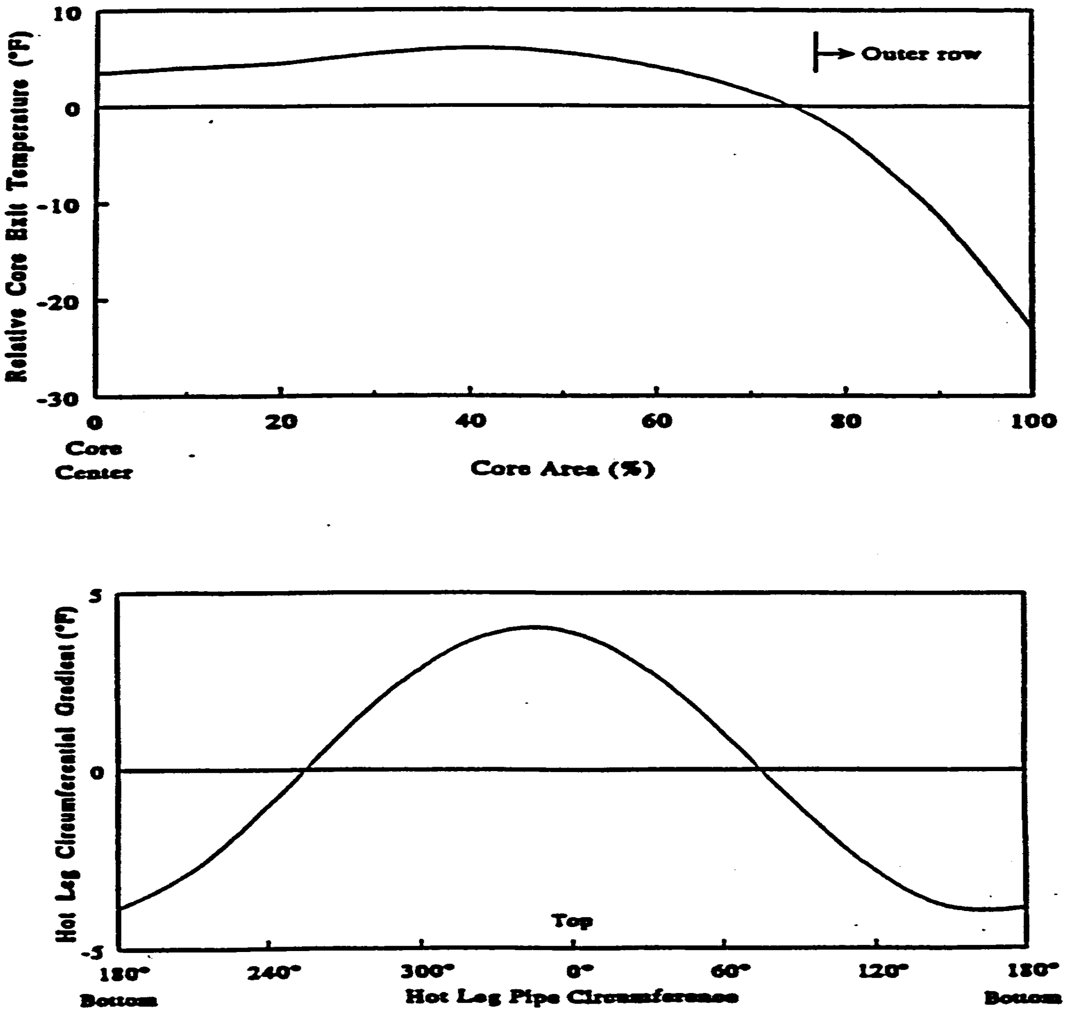

Figure 3-1 Typical Core Exit Temperature Gradient and RCS Hot Leg Circumferential Temperature Gradient

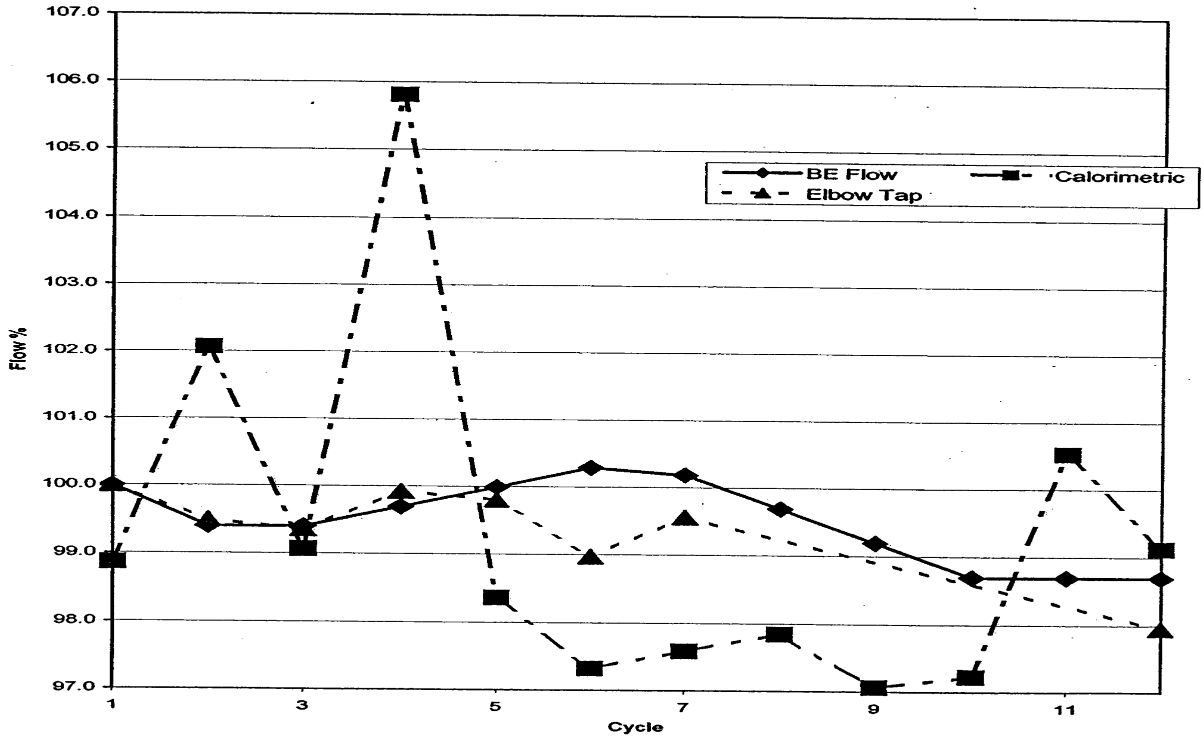

Figure 4-1 Yonggwang 2 Flow Comparisons

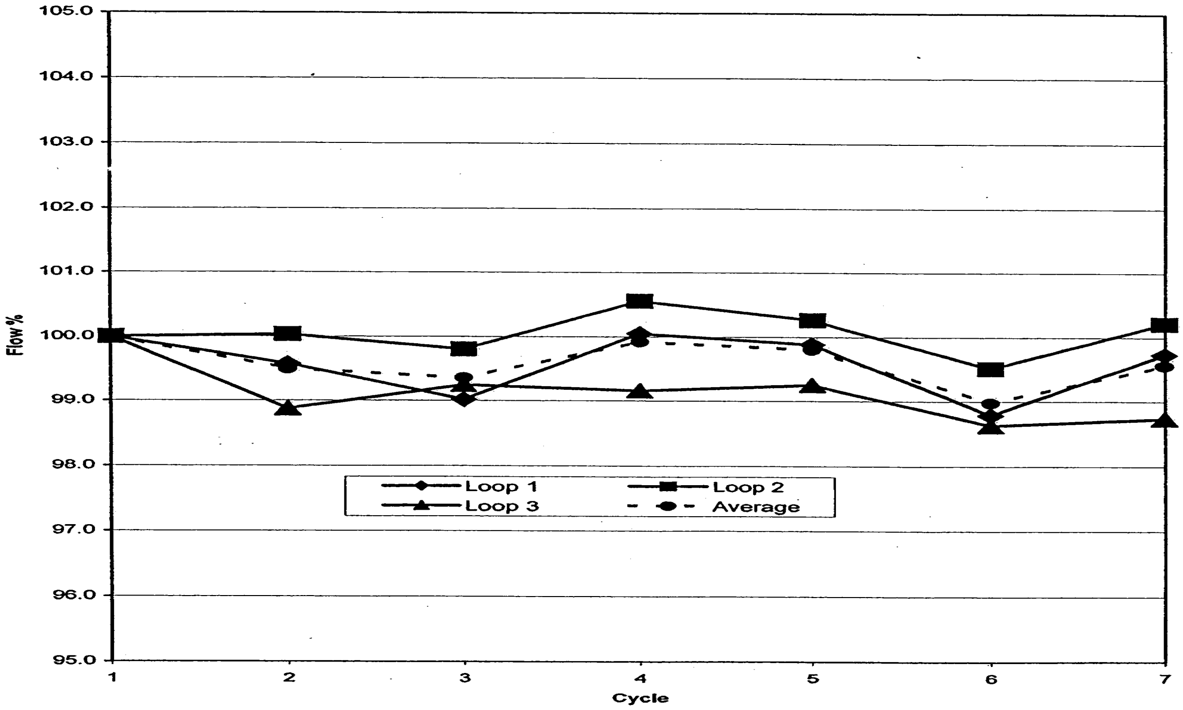

Figure 4-2 Yonggwang 2 Elbow Tap Flow
Normalized to Baseline Cycle 1

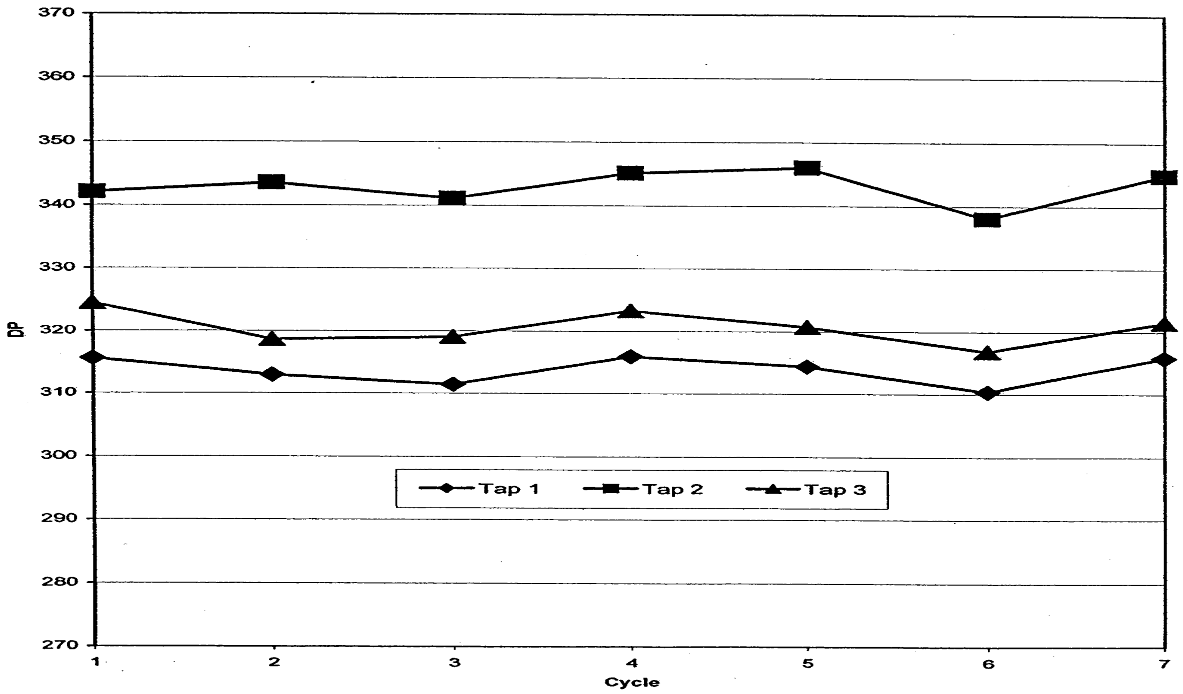

Figure 4-3 Yonggwang 2 Loop 1 Elbow Tap DP

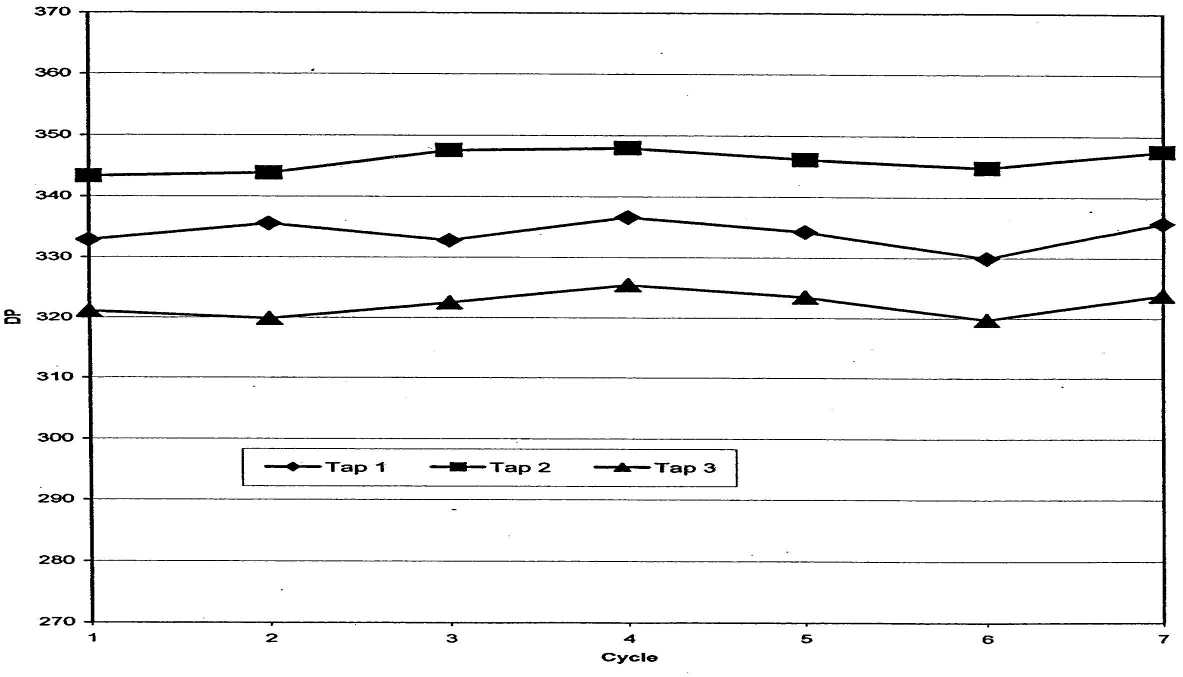

Figure 4-4 Yonggwang 2 Loop Elbow Tap DP

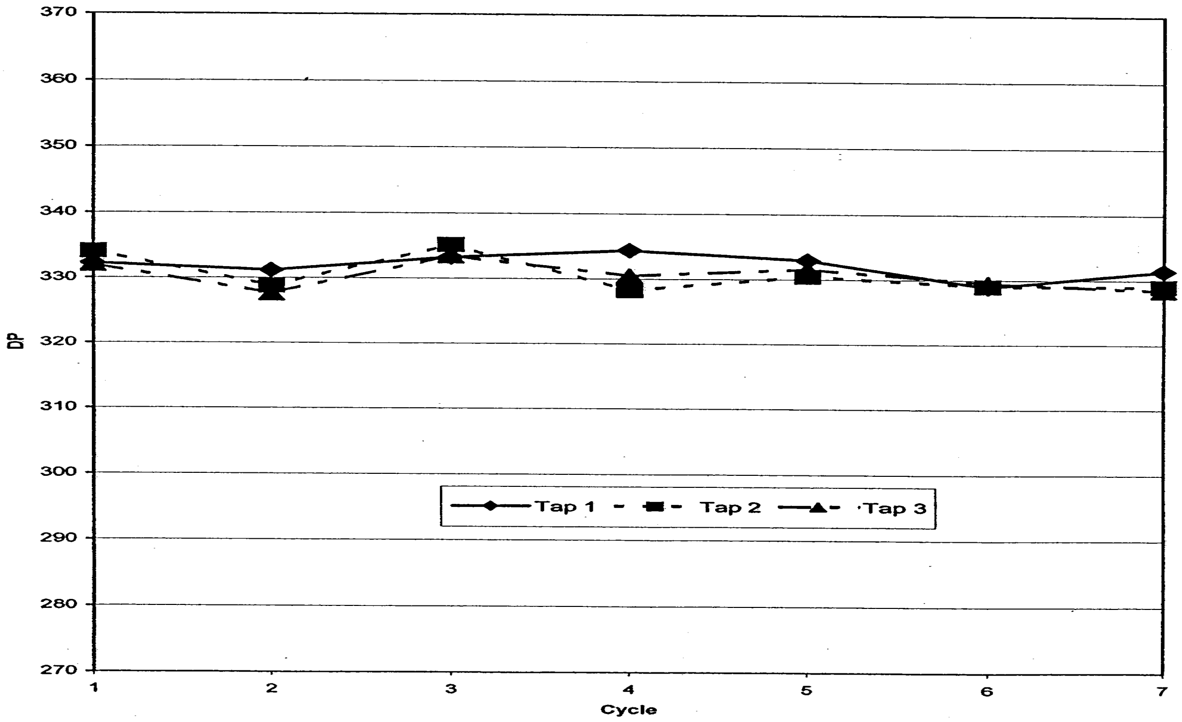

Figure 4-5 Yonggwang 2 Loop 3 Elbow Tap DP