July 1, 2003

Mr. G. R. Peterson
Vice President, Catawba Site
Duke Energy Corporation
4800 Concord Road
York, SC 29710

SUBJECT: CATAWBA NUCLEAR STATION, UNIT 2 RE: COLD LEG ELBOW TAP FLOW COEFFICIENTS

Dear Mr. Peterson:

By letters dated October 2, 2001, and March 19, 2003, the U. S. Nuclear Regulatory Commission (NRC) staff transmitted amendments to the Facility Operating License for the Catawba Nuclear Station, Unit 2, concerning the determination of reactor coolant system (RCS) flow rate. In the Safety Evaluations transmitted with those letters, the NRC staff stated that reactor coolant pump energy was incorrectly addressed in the Duke Power Company (Duke) application and that a correct calculation would provide a conservatism that Duke had not elected to take credit for. The NRC staff's conclusion, in this regard, was incorrect. The existing Duke calculations that supported the information provided to the NRC staff in the associated Duke submittals is correct. Since the error relates to an additional conservatism that was not incorporated into Duke's submittals to the NRC staff, the error does not affect the NRC staff's prior findings that the license amendment applications submitted by Duke are acceptable.

The error is related to the modeling of the thermodynamics of RCS flow. The enclosure discusses the validity of various modeling approaches and confirms the NRC staff's prior findings, issued on October 2, 2001, and March 19, 2003, that the license amendment applications submitted by Duke, are acceptable.

This information is provided to ensure that the record is correct on this issue. Please contact me at (301) 415-1493, if you have any other questions on these issues.

Sincerely,

/RA/

Robert E. Martin, Senior Project Manager, Section 1
Project Directorate II
Division of Licensing Project Management
Office of Nuclear Reactor Regulation

Docket No. 50-414

Enclosure: Supplement to Safety Evaluation

cc w/encl: See next page

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SUPPLEMENT TO SAFETY EVALUATION

BY THE OFFICE OF NUCLEAR REACTOR REGULATION

DETERMINATION OF REACTOR COOLANT SYSTEM FLOW RATE FROM A

CALORIMETRIC HEAT BALANCE ON THE SECONDARY SYSTEM

DUKE ENERGY CORPORATION

CATAWBA NUCLEAR STATION, UNIT 2

DOCKET NO. 50-414

1.0 SUMMARY

Reactor coolant system (RCS) flow rate is often determined by first performing a calorimetric heat balance on the secondary side to determine the heat transfer rate from the RCS into the steam generators (SGs). This heat transfer rate is then used in conjunction with RCS hot leg and cold leg temperature measurements to determine flow rate and to calibrate cold leg elbow tap flow meters. The Nuclear Regulatory Commission (NRC) staff recently completed two reviews of the determination of RCS flow rate for Duke Power Company's Catawba, Unit 2 (References 1 and 2). During further investigation of RCS flow rate, the NRC staff found an error in those reviews. Although the error does not change the NRC staff's finding of acceptability for the Duke Power amendment requests, it does involve modeling of the thermodynamics of RCS flow rate that should be clarified. This supplement to the previous safety evaluations, issued on October 2, 2001, and March 19, 2003, provides that clarification.

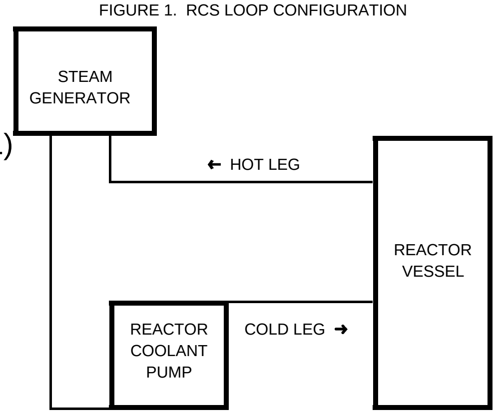
2.0 BACKGROUND

The RCS configuration illustrated in Figure 1 is typically used as a basis for flow rate analyses. An overall heat balance is taken over the control volume defined by the surface of the RCS to obtain Equation 1:

$$Q_{core} + Q_{RCP} - Q_{loss} = Q_{cal} \quad (1)$$

where: Q_{core} = nuclear heat generation rate in the core,
Q_{RCP} = rate of energy addition to RCS by reactor coolant pumps (RCPs),
Q_{loss} = net rate of RCS heat loss exclusive of SGs and RCPs, and
Q_{cal} = rate of heat removal by SGs.

FIGURE 1. RCS LOOP CONFIGURATION



This formulation assumes no mass transfer through the control volume surface[1] and the control volume is constant (the boundaries are rigid). Since Q_{cal} is determined from the calorimetric, and Q_{loss} and Q_{RCP} can be estimated, this equation will provide Q_{core}.

With Q_{core} determined, one may assume that mass flow rate through the core could be determined by dividing Q_{core} by the enthalpy difference across the core if the enthalpy difference were known. However, these enthalpies are not known because core inlet temperatures are not measured and there is a wide variation in core outlet temperatures with position across the top of the core. Consequently, it is necessary to make the determination where meaningful temperatures are measured. In practice, the hot and cold leg resistance temperature device (RTD) temperatures, T_h and T_c respectively, are used.

The NRC staff considers three different approaches to determine mass flow rate, M. The first is used in many typical fluid flow calculations. It simply assumes a constant pressure process with the following expression:

$$M = (Q_{core} - Q_{loss\Delta T}) / [C_p (T_{h} - T_c)] \qquad (2)$$

where: $Q_{loss\Delta T}$ = heat loss rate associated with all RCS components located between the cold and hot leg RTDs.

C_p = heat capacity at constant pressure.

Although it is not immediately apparent, Equation 2 does not correctly account for the effects of water flowing within the RCS between the measurement locations of T_c and T_h. This understanding is developed in Section 3, below.

The second approach depends upon the calculation of RCS pressures from an assumed RCS flow rate. With pressures determined, one can determine the hot and cold leg enthalpies, h_h and h_c respectively.[2] Then RCS flow rate in the hot and cold legs can be determined by the following relationship:

$$M = (Q_{core} - Q_{loss\Delta T}) / (h_h - h_c) \qquad (3)$$

This is the approach used by the Duke Power Company that the NRC staff discussed in References 1 and 2. Although not immediately obvious, it is shown in Section 3, below, that this is a thermodynamically correct representation that follows, in part, from the difference in hot

---

[1]A complete formulation must consider mass flow and all meaningful heat flows through the control volume boundary. This includes charging flow (+), letdown flow (-), seal injection flow (+), RCP thermal barrier cooler heat removal (-), pressurizer spray flow (-), pressurizer surge line flow (+), component insulation heat loss (-), component support heat loss (-), and control rod drive mechanism heat loss (-). The effect of these items is often incorporated into Q_{loss} a step that must be considered carefully if mass flow rates are involved.

[2]The initially determined RCS pressure distribution will be for an assumed RCS flow rate. Iteration to obtain a converged solution may not be necessary since enthalpy is a relatively weak function of pressure. However, there are situations where it may be necessary to iterate to obtain a converged solution.

and cold leg pipe diameters and the equal mass flow rates entering and leaving the control volume.

One can also assume RCP potential energy associated with the pressure increase at the RCP is converted to frictional heat throughout the RCS in direct proportion to the pressure drop.

Therefore, since the RCS pressure distribution is known as a function of M, the portion of RCP heat that is distributed between T_c and T_h, $Q_{RCP\Delta T}$, can be calculated and:

$$M = (Q_{core} + Q_{RCP\Delta T} - Q_{loss\Delta T}) / (h_h - h_c) \quad (4)$$

In Reference 1, the NRC staff estimated that the difference in M due to accounting for $Q_{RCP\Delta T}$ was 1450 gpm and the NRC staff concluded that the model represented by Equation 4 should be used. In Reference 3, the licensee agreed in principle with the NRC staff's determination, and calculated that failure to incorporate $Q_{RCP\Delta T}$ into the model under-predicted M by about 1045 gpm. The licensee elected to continue using Equation 3, the model without $Q_{RCP\Delta T}$, since it provided a conservative value of M. The NRC staff accepted this justification in Reference 2. The NRC staff now shows in Section 3, below, that Equation 4 is incorrect.

3.0 DISCUSSION

In the previous section, three typical approaches for determining RCS flow rate, M, were presented in Equations 2, 3 and 4. Each case is an implementation of Equation 1 using parameters measured in the plant or parameters that can be derived, such as the pressure distribution. Only Equation 3 is valid as is discussed below.

3.1 Thermodynamics of Fluid Flow

Equation 3 is a simplified expression of conservation of energy of a flowing system. This is shown to be the case by considering a general control volume and summing the forms of energy entering and leaving the volume through the control volume boundary:

heat + $[\text{mass flow rate}]_{in}$\{ internal energy + flow energy + kinetic energy + potential energy$\}_{in}$ =
work + $[\text{mass flow rate}]_{out}$\{ internal energy + flow energy + kinetic energy + potential energy$\}_{out}$,
or:

$$Q + M_{in} \{ u + [144 P V + v^2 / (2 g) + Z] / f \}_{in} = W + M_{out} \{ u + [144 P V + v^2 / (2 g) + Z] / f \}_{out} \quad (5)$$

where: Q = heat addition rate, Btu/sec
M = weight flow rate, lbs/sec
u = internal energy per unit weight, Btu/lb
P = pressure, lbs/in^2 absolute
V = volume per unit weight, ft^3/lb
v = velocity, ft/sec
g = gravitation constant, 32.2 ft/sec^2
Z = elevation, ft
f = conversion factor = 778 ft-lbs/Btu
W = work performed by the fluid, Btu/sec

Since, by definition, enthalpy is:

$$h = u + 144 \, P \, V / f \text{ (Btu/lb)} \qquad (6)$$

Equation 5 may also be written as:

$$Q + M_{in} \{ h + [v^2 / (2 g) + Z] / f \}_{in} = W + M_{out} \{ h + [v^2 / (2 g) + Z] / f \}_{out} \qquad (7)$$

Equation 7 may be applied to the RCS by selecting a control volume that encloses the reactor vessel and the pipes between the reactor vessel and the locations of T_h and T_c. There is no work done by the system within this control volume and W = 0. The hot and cold leg pipe elevations are identical and $Z_{in} = Z_{out}$. There is no accumulation of mass and $M_{in} = M_{out} = M$. We will also assume that $v_{in} = v_{out}$. This velocity assumption is, of course, a simplification but because the heat addition is large, and the differences in hot and cold leg velocity are small (because of the increase in hot leg diameter that accommodates the decrease in fluid density), the error introduced by this simplification is negligible. Equation 7 therefore reduces to:

$$Q + M \, h_c = M \, h_h \qquad (8)$$

But Q is Q_{core} minus that portion of Q_{loss} associated with the reactor vessel and the pipes between locations of T_h and $T_{c,}$ $Q_{loss\Delta T}$. Thus,:

$$M = (Q_{core} - Q_{loss\Delta T}) / (h_h - h_c) \qquad (9)$$

Since T_h and T_c are measured, and P_h and P_c are known as a function of M, h can be obtained from known water properties. Thus, Equation 9 will provide M.

Equations 9 and 3 are identical. Consequently, the NRC staff’s conclusion, reached in Reference 1 that Equation 4 was a better representation of the behavior than Equation 3 is incorrect.

Thermodynamically, the enthalpy terms in Equation 9 (and Equation 3) address the energy transition between potential energy and thermal energy. Q_{RCP} is not modeled because the pump energy is added to the system outside the control volume by accounting for the pressure rise, inefficiency, and velocity changes across the pump. Since the process is not modeled as isobaric, enthalpy is a function of both pressure and temperature. Therefore, the enthalpy addition stemming from the increase in pressure across the pump is accounted for within the control volume and does not have to be incorrectly modeled as a heat addition term as is done in Equation 4.

3.2 Hot Leg and Cold Leg Flow Velocities

Now the assumption that $v_{in} = v_{out}$ is examined by calculating RCS behavior using the flow model described in Reference 4 to provide the pressure distribution throughout the RCS for a flow rate of 100,476 gpm (10337 lbs/sec) in one loop with T_h = 620 °F. All control volumes are selected so that Z is constant and the assumption is made that $Q_{loss} = 0$ to simplify the calculation. The calculation path is summarized in Table 1. The path is initiated at the hot leg where temperature and pressure are known so that fluid properties can be calculated. (Knowledge of two properties is both necessary and sufficient for determination of all properties in a single component, single phase fluid.) It is now assumed that cold leg pressure is known and an assumption is made of an isenthalpic compression from the hot leg conditions to obtain the cold leg conditions. The process of working backward is continued to obtain RCP discharge conditions. Then RCP suction conditions can be calculated by considering the pump in steps as an isentropic process, heat addition to account for inefficiency, and a kinetic energy change due to velocity change. The flow is assumed to be isenthalpic to obtain properties in the pipes at the exit and entrance of the steam generator. The kinetic energy change at the RCP and at the SG is essentially the same; 0.25 MW. This is added to the fluid energy at the RCP to obtain the total RCS energy, and subtracted during the energy balance at the SG to obtain the heat removed from the RCS at the SG.

Table 1. Calculation Path Assumptions

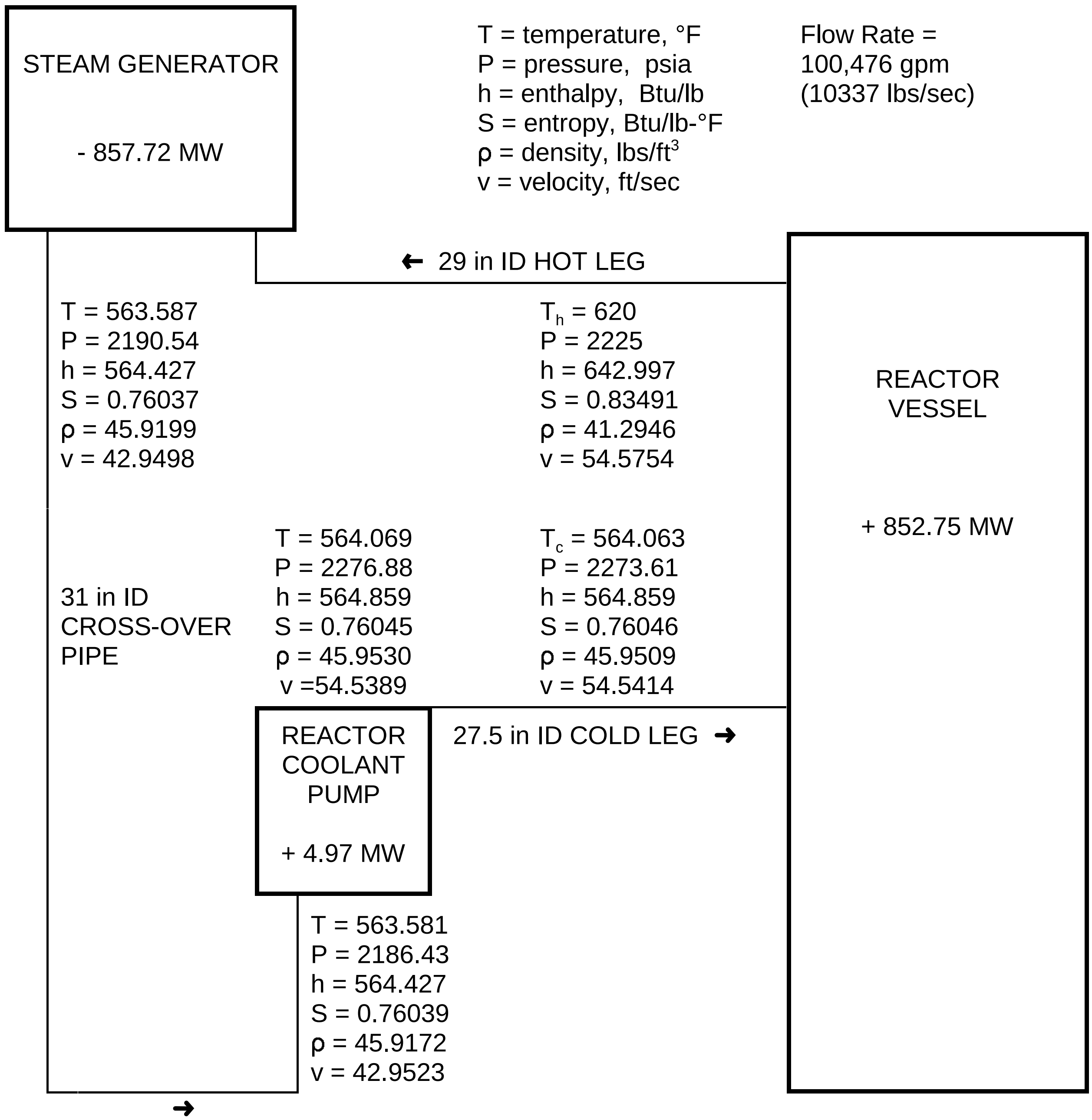
RCS Location	Known P, psia	Process and/or comments
Hot leg at T_h	2225	Physical properties, including h, known from known P and 620 °F temperature via steam tables
		Isenthalpic compression to 2273.61 psia, decrease h by 862.75 MW core heat
Cold leg at T_c	2273.61	Properties from known h and 2273.61 psia
		Isenthalpic compression to 2276.88
RCP exit	2276.88	Properties determined by above known h and 2276.88 psia
		Assume pump is represented by of heat addition, isentropic compression, and incorporation of kinetic energy
		Decrease h by assumed RCP inefficiency of 0.7 MW at constant P to get new h; known P determines new properties
		Decompress via isentropic expansion to 2186.43 psia
RCP entrance	2186.43	Properties determined by known entropy and 2186.43 psia
		Isenthalpic compression to 2190.54 psia
Steam generator (SG) exit	2190.54	–
Hot leg at T_h	2225	
		Isenthalpic decompression to 2223.94 psia
SG entrance	2223.94	Properties determined by known h and 2223.94 psia

The results are summarized in Figure 2. The results demonstrate that v_c and v_h are essentially equal, confirming the assumption used to obtain Equation 8.[3] Note that this is not true for flow

[3]The velocities could have been determined by a simple calculation based on known P, T, and flow area at T_c and T_h. We used the above approach because it introduces additional characteristics that are of interest.

through the RCP and through the SG, where the velocity increases from 42.9523 ft/sec to 54.5389 ft/sec and decreases from 54.5754 ft/sec to 42.9498 ft/sec, respectively.

FIGURE 2. THERMODYNAMIC ANALYSIS OF RCS

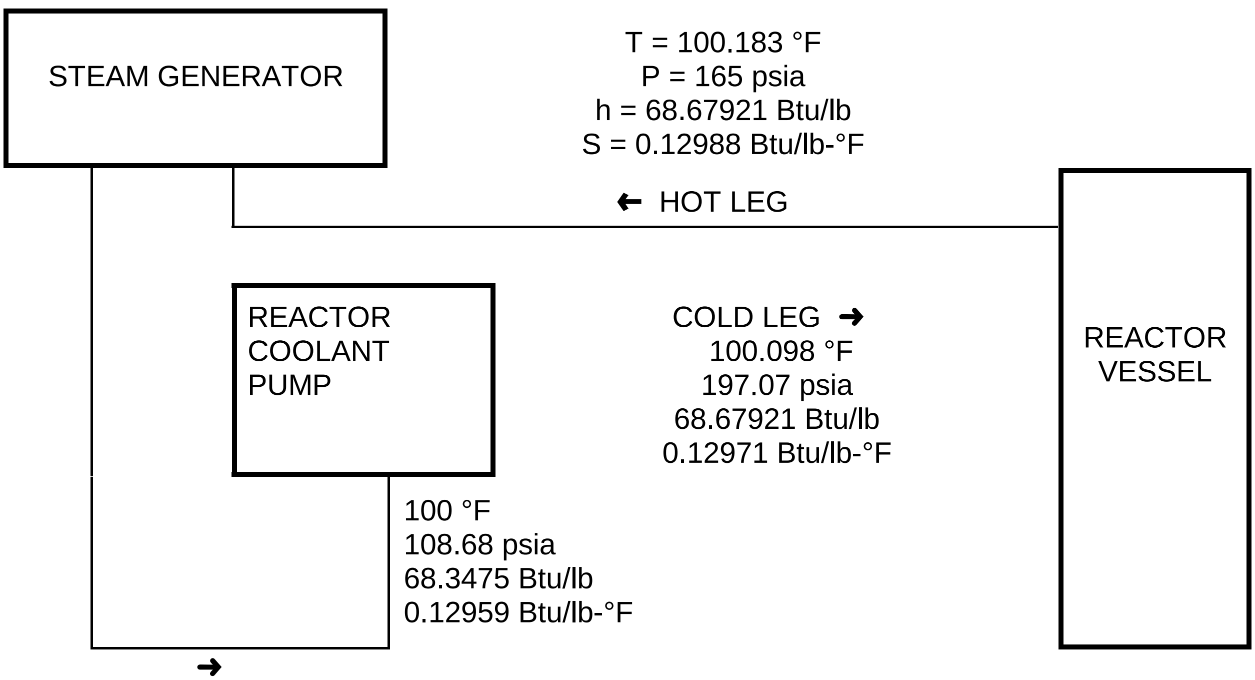


3.3 An Anomaly: RCS Water Cools Due To Friction

The Figure 2 results refute the generally accepted conclusion that in a flowing system with a viscous fluid, frictional pressure drop causes the fluid temperature to increase, as assumed in Equation 4. The reverse behavior is illustrated in Figure 2 where, for example, temperature decreases from 563.587 °F at the SG outlet to 563.581 °F at the RCP inlet.

To address this apparent anomaly, consider the calculation results summarized in Figure 3 for conditions at roughly 100 psia and 100 °F with the additional assumption of no core heat addition. In this case, the temperature increases from T_c = 100.098 °F to T_h = 100.183 °F, as intuitively expected.

FIGURE 3. RCS BEHAVIOR AT LOW PRESSURE



The NRC staff concludes that a thermodynamically based calculation yields the expected temperature behavior when temperature and pressure are relatively low, but the reverse occurs at typical RCS operating conditions. Such behavior is typical of the Joule-Thomson throttling process where Δh = 0. The behavior is described by the Joule-Thompson coefficient:

$$\mu = (\partial T / \partial P)_h \tag{10}$$

The condition where μ = 0 represents the inversion temperature. The throttling process will result in cooling if μ > 0 and in heating if μ < 0. Therefore, the sign of the Joule-Thompson coefficient has reversed when changing the process from water near room temperature conditions to typical RCS operating conditions. Although not expected from our experience, in part because the effect is small, the results are consistent with theory.

3.4 RCS Heat Loss Rate

Next, the effect of heat loss is considered. It would be expected that the RCS heat loss rate is about 25 percent of the RCP heat, or about 1.25 MWt per loop (including 1/4 of the reactor vessel per loop). As an estimate, assume about half of this heat is lost as the water flows from the location of T_c to the location of T_h. When compared to the adiabatic case, this will reduce the Figure 2 $T_h - T_c$ by about 0.066 °F and will increase the calculated flow rate for four loops by about 340 gpm.

Failure to include heat loss will decrease calculated core heat generation rate by about 0.16 percent (see Equation 1) and will decrease predicted flow rate by about 0.08 percent (see Equation 3). Hence, failure to include heat loss rate will under-predict the RCS flow rate, a conservatism.

3.5 The Effect of Thermal Power

Some calorimetric determinations are done at less than 100 percent core power. To assess this situation, Equation 7 is applied with the assumptions of no change in M, Z, and W, to obtain:

$$Q + M \{ h + v^2 / (2 g f) \}_{in} = M \{ h + v^2 / (2 g f) \}_{out} \quad (11)$$

or:

$$M = (Q_{core} - Q_{loss\Delta T}) / [h_h - h_c + (v_h^2 - v_c^2) / (2 g f)] \quad (12)$$

Taking $Q_{loss\Delta T} = 0$, assuming an isenthalpic expansion from T_c to T_h, and adding Q_{core}, h_h can be obtained if h_c is known, and h_c can be determined if T_c and P_c is known. Consequently, it is assumed as a first step that the pressure distribution is the same as used in development of Figure 2 and behavior as a function of Q_{core} is examined with the average of T_h and T_c approximately constant. The calculations and results are provided in Table 2. The results show that power level has no practical influence on the RCS flow rate if the RCS pressure distribution is assumed constant. (Note, this does not address the accuracy of the calorimetric determination. In general, accuracy will diminish as power level approaches a small value.)

In Reference 5, Duke Power showed that a variation in power from zero to 100 percent changed flow rate by about 4000 gpm (1000 gpm per loop) as measured by elbow tap flow meters. Although this will have some effect on pressure distribution throughout the RCS, the NRC staff does not believe it would have a significant effect on the tabulated comparison conclusions.

Table 2. Effect of Power Variation on Determination of RCS Flow Rate

Item	100% Power	90% Power	80% Power
T_c	564.063	566.8	569.6
h_c	564.859	568.336	571.997
ρ_c	45.9509	45.7625	45.5669
v_c	54.5414	54.7656	55.0010
T_h	620	617.202	614.484
h_h	642.997	638.660	634.508
ρ_h	41.2946	41.5779	41.8457
v_h	54.5754	54.2035	53.8567
$(v_h^2 - v_c^2) / (2 g f)$	0.00007	-0.00122	-0.00249
M	10337.4	10337.6	10337.7
M @ $\Delta v = 0$	10337.0	10337.4	10337.3

3.6 Comparison of Equations 2 and 3

Two equations were previously provided that differed in the calculation of heat from a temperature determination:

$$M = (Q_{core} - Q_{loss\Delta T}) / [C_p (T_h - T_c)] \quad (2)$$

and:

$$M = (Q_{core} - Q_{loss\Delta T}) / (h_h - h_c) \quad (3)$$

The NRC staff further concluded that Equation 3 is correct if values of h are determined from T and P. As seen from the above Section 3 discussion, thermodynamic considerations yield Equation 3 as a solution. For Equation 2 to be correct, it would be necessary for $C_p (T_h - T_c)$ to equal $h_h - h_c$. The effect of pressure can be illustrated by considering the typical engineering calculation process of using tabulated values corresponding to saturation temperature. At 610 °F and the saturation pressure of 1665 psia, h = 631.568 Btu/lb. At 2225 psia and 610 °F, h = 627.782 Btu/lb, a significant difference. This is an indication that enthalpy is a function of pressure and that assuming a constant pressure process is inaccurate. Consequently, use of C_p is questionable.

3.8 Assessment of Reference 1 and 2 Reviews

References 1 and 2, and the Duke Power Company documentation reviewed in support of those references, did not identify whether Equation 2 or Equation 3 was used to calculate RCS flow rate. This was covered in previous documentation, such as Reference 6, and established that the correct Equation 3 was used.

As discussed in Reference 2, Duke Power Company elected not to credit the additional flow rate that would have been provided via application of Equation 4. The NRC staff noted this several times in its review by crediting this perceived margin. The most specific reference was the Section 3.3.4 statement that not correcting "for the RCP thermal energy error of about 1045 gpm ... clearly compensates for any NRC staff concerns regarding the effect of impeller smoothing." In the same section, the NRC staff also stated that there was a change of 1000 gpm over the time span applicable to the licensee's selection of the September 1986, November 1986, and March 1988 calorimetrics for determination of elbow tap coefficients that introduces a conservatism. In Section 3.3.1.1, the NRC staff referenced the licensee's estimate that the selected calorimetrics introduced a 1500 gpm conservatism and, although the NRC staff did not specifically prove the licensee's value to be correct, the NRC staff provided additional insights to support the conservatism. The licensee additionally selected cold leg RTDs that introduced close to 2000 gpm additional conservatism when compared to selection of normal cold leg RTDs. These licensee selections establish that there is sufficient conservatism to address uncertainties associated with flow rate determination. Consequently, with the exception of the statement that failure to correct for RCP heat was an error, the Reference 2 findings remain valid.

4.0 CONCLUSIONS

The Reference 1 and NRC reviews of Duke Power Company's determination of RCS flow rate contain an error. The NRC staff stated that RCP energy was incorrectly addressed and that a correct calculation would provide a conservatism that Duke elected not to credit. The NRC staff's conclusion was incorrect. The existing Duke calculation is correct. Other conservatisms remain and the NRC staff's finding of acceptability of the Duke Power amendment requests remain valid.

A thermodynamically-based assessment of RCS flow rate yielded several behavioral insights that were not immediately evident. These include:

1. Use of enthalpies in the RCS heat balance equations provides a correct accounting for RCP heat input and no corrections are necessary.

2. RCS design results in essentially equal hot and cold leg velocities so that there is no change in kinetic energy when comparing behavior at the hot and cold leg temperature measurement locations.

3. With the exception of the RCPs, the intuitive perception that RCS water temperature will increase due to friction during flow is incorrect. There is actually a slight decrease in temperature, an effect due to a positive Joule-Thompson coefficient for water at full power operating conditions. This condition does not exist at low temperature conditions typical of Mode 4 operation.

5.0 REFERENCES

1. Patel, Chandu P., "Catawba Nuclear Station, Unit 2 Re: Issuance of Amendment (TAC No. MB1498)," NRC letter to Duke Energy Corporation, October 2, 2001.

2. Martin, Robert E., "Catawba Nuclear Station, Unit 2 Re: Issuance of Amendment, Cold Leg Elbow Tap Flow Coefficients (TAC No. MB6529)," NRC letter to Duke Energy Corporation, March 19, 2003.

3. Peterson, Gary R., “Duke Energy Corporation, Catawba Nuclear Station, Unit 2, Docket Number 50-414, Proposed License Amendment for Unit 2 Reactor Coolant System Cold Leg Elbow Tap Flow Coefficients,” Duke letter to NRC, October 10, 2002.

4. Peterson, Gary R., “Duke Energy Corporation, Catawba Nuclear Station, Unit 2, Docket Number 50-414, Response to Request for Additional Information for Unit 2 Reactor Coolant System Cold Leg Elbow Tap Flow Coefficients,” Duke letter to NRC, February 7, 2003.

5. Peterson, Gary R., “Duke Energy Corporation, Catawba Nuclear Station, Unit 2, Docket Number 50-414, Response to Request for Additional Information for Unit 2 Reactor Coolant System Cold Leg Elbow Tap Flow Coefficients,” Duke letter to NRC, February 26, 2003.

6. Martin, Robert E., “Summary of February 10, 1994, Meeting with Duke Power Company on RCS Flow Measurement Methodology,” NRC, April 13, 1994.

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