

**Follow up Audit Question 16 Clarification  
on NRC NPSH question**

### **NRC Request for Additional Information:**

For the pumps that draw water from the sump during the loss-of-coolant accident (LOCA) recirculation phase, the sump temperature response and pump flow affects their available NPSH and required NPSH respectively. Provide the revised NPSH analysis, if exists, including containment accident pressure used to confirm positive NPSH margin for those pumps.

### **Response to NRC Request for Additional Information:**

The Residual Heat Removal (RHR) pumps and Containment Spray (CS) pumps both draw water from the sump during the loss-of-coolant accident (LOCA) recirculation phase in the Callaway plant design. The relevant NPSH calculations for each pump are identified and summarized. The NPSH calculations for both sets of pumps account for sump water temperature and the NPSH calculations for both sets of pumps do not take credit for containment overpressure as a benefit in available NPSH. The impact of increased pump speed associated with variations in diesel generator voltage and frequency is evaluated.

### **Containment Spray Pump**

#### **NPSH Calculation Summary**

Calculation EN-13, "NPSH Margin for Containment Spray Pumps at transition to Recirculation When NPSH Margin is at its Minimum Value" determines the net positive suction head (NPSH) available and the NPSH required for the containment spray (CS) pumps during the transition from injection to recirculation when NPSH margin is at its minimum value. The following important assumptions are made in EN-13 to minimize available NPSH and maximize required NPSH:

- Since containment spray can reach the maximum recirculation flow rate following either a large break LCOA or main steam line break accident, the minimum flood elevation at swap over from both of these cases is considered. The lowest flood elevation in containment will be used since that will minimize the static head contribution to NPSH available for the CS pumps.
- At the time of swap over to recirculation, the sump fluid temperature is expected to be less than 270 °F; however, 270 °F is chosen as an upper bounding temperature for this analysis. The maximum safeguards case yields lower temperatures and significantly higher flood levels post-accident. A lower temperature of 205 °F is chosen to bound the lower temperature cases.
- Credit is not taken for the containment overpressure. The vapor pressure of the liquid in the sump will be assumed to equal the containment pressure. This ensures that the actual available NPSH is greater than the calculated NPSH.
- The design flow rate for the containment spray pumps is given in calculation M-EN-40 Rev. 0 as Design CS Pump Flow = 3750 gpm. Calculation M-EN-40 Rev. 0 evaluates a conservative maximum recirculation flowrate by reducing system resistance by 10% and crossing this curve with the system performance curve. The maximum containment spray pump flow rate provided in M-EN-40 Rev. 0 as CS Pump Flow Assumed to Assure 10% margin in NPSH is 3950 gpm. Calculation EN-13 notes that the actual pump operating point (system resistance crosses pump curve) appears to show a flow rate of approximately 3825 gpm on page 5 in calculation M-EN-34 Rev. 0. Considering an eductor recirc flow of about 75 gpm (see page 15 in M-EN-34 Rev. 0) the delivered

flow would be about 3750 gpm (i.e. flow without margins). To maximize the calculated piping friction losses, a maximum CS pump flow rate of 3950 gpm is used herein, with an assumption of 73 gpm flowing through the eductor which assumes a delivered flow of 3877 gpm.

The minimum available NPSH during transition to recirculation is calculated as follows:

$NPSH = \text{Pressure Head (ft)} + \text{Static Head (ft)} - \text{Friction Loss (ft)} - \text{Vapor Pressure (ft)} \text{ at saturated temperature}$

Since it is assumed that Pressure Head (ft) = Vapor Pressure (ft) at saturated temperature; this simplifies to:

$NPSH = \text{Static Head (ft)} - \text{Friction Loss (ft)}$

The friction losses are conservatively rounded up to the values listed below :

- Friction loss assuming 3950 gpm in piping and 205 °F with additional margin added= 3.4 psi (Calculation EN-13 Rev. 0)
- Friction loss assuming 3950 gpm in piping and 270 °F with additional margin added= 3.5 psi (Calculation EN-13 Rev. 0)

The friction losses are converted to feet:  $\text{Loss (feet)} = [\text{Loss (Lb/in}^2)] \cdot [\text{Specific volume (ft}^3/\text{Lb)}] \cdot [144 \text{ (in}^2/\text{ft}^2)]$

- Friction loss at 205 °F =  $(3.4 \text{ psi}) \cdot (0.016668 \text{ ft}^3/\text{lb}) \cdot (144 \text{ in}^2/\text{ft}^2) = 8.401 \text{ feet}$
- Friction loss at 270 °F =  $(3.5 \text{ psi}) \cdot (0.01717 \text{ ft}^3/\text{lb}) \cdot (144 \text{ in}^2/\text{ft}^2) = 8.406 \text{ feet}$

Since the minimum flood height at CS post-LOCA is slightly lower than the flood height post-MSLB, it will be used to bound both scenarios. Minimum flood height is at CS swap over post-LOCA max safeguards case:

Sump water level = 2002.33 ·ft

The pump discharge elevation centerline is 1971' 0-3/4" as shown on M-23EN01 Rev. 7 for PEN01A and M-23EN02 Rev. 12 for PEN01B.

$h_{\text{discharge}} = 1971.0625 \cdot \text{ft}$

$NPSH = \text{Static Head (ft)} - \text{Friction Loss (ft)}$

At 270°F,  $NPSHA_{270^\circ\text{F}} = 2002.33 \text{ ft} - 1971.0625 \text{ ft} - 8.406 \text{ ft} = 22.111 \text{ ft}$

At 205°F,  $NPSHA_{205^\circ\text{F}} = 2002.33 \text{ ft} - 1971.0625 \text{ ft} - 8.401 \text{ ft} = 22.117 \text{ ft}$

The required NPSHR is taken from FSAR Figure 6.2.2-5:

$NPSHR := 16.5\text{-ft}$

The available NPSH is approximately 22.1 ft. The required NPSH is approximately 16.5 ft. The available NPSH margin is acceptable considering a sump temperature range of 205 °F to 270 °F. There is sufficient design margin considered in the above calculation to accommodate minor changes in input assumptions.

### **NPSH Impact Due to Deisel Generator Frequency and Voltage Variations**

The pump affinity laws indicate that as pump speed increases the pump performance changes in the following manner:

- Pump flow rate and pump efficiency increase linearly with speed,
- pump developed head and required NPSH increase by the square of the speed, and
- pump power increases by the cube of speed.

The existing calculations discussed previously do not address changes in pump speed. It is shown below that the conservative flow rate of 3950 gpm used to calculate available NPSH remains valid if pump speed increases due to diesel generator frequency and voltage. It is noted the higher frequency case is the bounding as pump speed increases as frequency increases and NPSH required is proportional to the square of pump speed. Therefore, NPSH required will decrease at lower pump speeds and the NPSH available from the system would remain virtually the same. It is shown that the increase in pump speed will be at most 0.9% resulting in an increase of NPSHR by 1.9%, changing the required NPSH from 16.5 feet to 16.8 feet. The NPSH margin is reduced from 22.1-16.5 = 5.6 feet to 22.1 – 16.8 = 5.3 feet. It is concluded that the available NPSH margin of approximately 5.3 ft is acceptable.

The containment spray pump curves for Callaway are Ingersoll Rand Pump Curve No. 971, Containment Spray Pump A, Pump No. 097636, 8x23 WDF, December 8, 1977, and Ingersoll Rand Pump Curve No. 972, Containment Spray Pump B, Pump No. 097637, 8x23 WDF, December 15, 1977. The performance of these pumps is compared in Table 1. Spray pump B has a stronger pump curve and the points in Table 1 are fit to the following quadratic equation.

$$\Delta H_{pump} = 532.73 + (9.4487E - 03)Q - (9.5022E - 06)Q^2$$

The pump head at the design flow rate of 3750 gpm is 434.54 feet using this formula.

Bechtel Calculation EN-31, "CTMT Spray Header Balance Calc," Revision 0, indicates the elevation of the lowest spray ring is at 2165'-8" and the highest elevation ring is at 2203'-7". Using the NPSH sump water level as 2002.33, the elevation head which the pumps must offset varies between:

$$\Delta H_{Elev} = 2165.67 - 2002.33 = 163.34 \text{ ft and } \Delta H_{Elev} = 2203.58 - 2002.33 = 201.25 \text{ ft}$$

The calculations which follow assume all spray nozzles are at an elevation head of 163.34 feet since the greatest number of nozzles are at this elevation and it results in a largest flow impact due to pump speed change. If it is assumed that all spray nozzles are at an elevation head of 201.25 feet, the system resistance decreases from the value of  $2.00806 \times 10^{-5} \frac{ft}{gpm^2}$  provided below to  $1.7273 \times 10^{-5} \frac{ft}{gpm^2}$  and the pump flow in Table 2 changes from 3933.52 gpm to 3931.90 gpm. This demonstrates the change is small and the calculations shown are conservative.

The head loss due to frictional and form losses is the difference between the pump head and the elevation head. Consistent with the previous discussion for CS pump NPSH flow, an eductor recirc flow of 75 gpm is assumed. Therefore, the design spray flow rate is the design pump flow rate minus the eductor flow rate, or 3750-75=3675 gpm.

The design spray resistance is calculated as:

$$K_{Design} = \frac{\Delta H_{Loss}}{Q_{spray}^2} = \frac{\Delta H_{Pump} - \Delta H_{Elev}}{Q_{spray}^2} = \frac{434.54 - 163.34}{(3675 \text{ gpm})^2} = \frac{271.20 \text{ ft}}{(3675 \text{ gpm})^2} = 2.00806 \times 10^{-5} \frac{\text{ft}}{\text{gpm}^2}$$

Table 2 is used to predict the effect of increased pump speed on spray flow rate. The values of  $\Delta H_{Elev} = 163.34 \text{ ft}$ ,  $Q_{eductor} = 75 \text{ gpm}$  and a resistance reduction factor,  $F_{RR}=0.9$  are held constant for each case in Table 2. The following values are calculated as  $Q_{spray}$  is varied until  $\Delta H_{Balance} = 0 \text{ ft}$ .

$$Q_{Pump} = Q_{spray} + Q_{Eductor}$$

$$\Delta H_{Loss} = F_{RR} K_{Design} Q_{spray}^2$$

$$\Delta H_{Pump} = 532.73 + (9.4487E - 03)Q_{Pump} - (9.5022E - 06)Q_{Pump}^2 + \Delta H_{Correction}$$

$$\Delta H_{Balance} = \Delta H_{Pump} - \Delta H_{Loss} - \Delta H_{Elev}$$

1. The first column of Table 2 demonstrates the effect of a 10% reduction in system resistance. This is incorporated by multiplying the design resistance by a resistance reduction factor  $F_{RR}=0.9$ . The spray flow is calculated as 3811.7 gpm and the pump flow is 3886.7 gpm. This is higher than the value of 3825 gpm provided in calculation EN-13 but still allows margin to the NPSH pump flow of 3950 gpm used in EN-13.
2. The second column addresses the speed increase of the pump. LTR-SEE-18-228, Rev. 2, indicates the nominal speed of the spray pump is 1770 rpm and the uncertainty in speed due to frequency and voltage uncertainties is 16.78 rpm. LTR-SEE-18-228 also indicates that the maximum change in CS pump head is 9.53 feet due to this change in speed. The pump head correction value is provide as  $\Delta H_{Correction} = 9.53 \text{ feet}$ . A spray flow rate of 3858.5 gpm and a pump flow of 3933.5 gpm are the converged values and demonstrate that including the 10% reduction in resistance and the head increase due to speed change still results in a pump flow rate bounded by the NPSH limit of 3950 gpm.

It is concluded that the conservative flow rate of 3950 gpm used to calculate available NPSH remains valid if pump speed increases due to diesel generator frequency and voltage change. The percent increase in pump speed is:

$$\% \text{ speed change} = 100 \left( \frac{16.78 \text{ rpm}}{1770 \text{ rpm}} \right) = 0.948$$

Since the required NPSH is assumed to vary with speed squared, the revised NPSH will be:

$$NPSHR_{1786.78 \text{ rpm}} = 16.5 \left( \frac{1786.78 \text{ rpm}}{1770 \text{ rpm}} \right)^2 = 16.81 \text{ feet}$$

$$NPSH \text{ margin at } 1786.78 \text{ rpm} = 22.11 \text{ feet} - 16.81 \text{ feet} = 5.3 \text{ feet}$$

CSS A vendor			CSS B vendor	
Pump Flow	Pump Head		Pump Flow	Pump Head
(gpm)	(feet)		(gpm)	(feet)
0	530.1		0	537.1
500	525.9		500	532.9
1000	521.6		1000	528.6
1500	515.7		1500	522.7
2000	506.6		2000	513.6
2500	492.8		2500	499.8
3000	472.6		3000	479.6
3500	444.6		3500	451.6
4000	407.1		4000	414.1

		Calculation Description	10% Resistance Reduction	Speed increase with 10% Resistance Reduction
$\Delta H_{Elev}$	feet	Constant value of 163.34 ft	163.34	163.34
$Q_{spray}$	gpm	Solved by iteration until $\Delta H_{Balance} = \Delta H_{Pump} - \Delta H_{Elev} - \Delta H_{Loss} = 0$	3811.68	3858.52
$Q_{ed}$	gpm	Constant value of 75 gm	75	75
$Q_{pump}$	gpm	$Q_{Pump} = Q_{Spray} + Q_{eductor}$	3886.68	3933.52
$K_{Design}$	ft / (gpm) <sup>2</sup>	$2.00806E-05$ ft / (gpm) <sup>2</sup>	$2.00806E-05$	$2.00806E-05$
$F_{RR}$		Specified for each case	0.9	0.9
$\Delta H_{Loss}$	feet	$\Delta H_{Loss} = K_{Design} F_{RR} Q_{Spray}^2$	262.57	269.06
$\Delta H_{Correction}$	feet	$\Delta H_{Correction}$	0	9.53
$\Delta H_{Pump}$	feet	$\Delta H_{Pump} = A Q_{Pump}^2 + B Q_{Pump} + C + \Delta H_{Correction}$	425.91	432.40
$\Delta H_{Balance}$	feet	$\Delta H_{Balance} = \Delta H_{Pump} - \Delta H_{Elev} - \Delta H_{Loss}$	0	0

## Residual Heat Removal Pumps

The RHR pumps operate in two different alignments when they draw water from the containment sumps: cold leg recirculation (*Figure 1*) and hot leg recirculation (*Figure 2*). At the end of the injection mode of operation, the system is initially aligned for cold leg recirculation. The limiting margin for available RHR pump NPSH occurs during the recirculation phase at the time of ECCS pump suction swap over from RWST to the containment recirculation sumps. The sump water elevation is at its minimum level since not all the emergency core cooling water sources [Refueling Water Storage Tank (RWST) and safety injection accumulator tanks] along with spilled reactor coolant system (RCS) water inventory have discharged and migrated to the containment sump. The acceptance criteria for this calculation is that the available NPSH shall exceed the required NPSH for the RHR pumps (Ref. "Net Positive Suction Head" section of FSAR SP 6.3.2.2).

The limiting RHR pump required NPSH configuration occurs when only one RHR pump is operating. In the limiting cold leg recirculation configuration, one RHR pump takes suction from the sump and delivers flow directly to two RCS cold legs and feeds two centrifugal charging pumps (CCPs) and two safety injection pumps (SIPs), both of which are injecting flow to the cold legs. In the cold leg recirculation configuration, both CCPs inject water into the RCS cold legs through a common header and both SIPs inject water into the RCS cold legs through a common header. This significantly reduces the maximum flow rate supplied by the CCPs and SIPs due to the increased hydraulic losses associated with shared piping and minimizes the required NPSH.

In the hot leg recirculation configuration, both CCPs continue to inject water through a common header to the cold legs, but each SIP is now aligned with its own hot leg injection header. Therefore, the maximum flow rate supplied by each SIP can exceed its maximum flow rate during cold leg injection mode of operation. Therefore, the hot leg recirculation configuration typically results in the most limiting required NPSH since the RHR pump flow rate is typically higher in this mode than in the cold leg recirculation mode.

Acceptability of pump available NPSH from the containment sump for Callaway was demonstrated using Calculation EJ-29, Rev. 002, "Residual Heat Removal Pump NPSH Margin During Recirculation." These calculations determine the Net Positive Suction Head (NPSH) margin for the Residual Heat Removal (RHR) pumps, PEJ01A/B, during the recirculation mode of operation under varying sump water levels and sump fluid temperatures. These calculations reflect the hydraulic changes to the Containment Recirculation Sump strainers (FEN01 A/B) implemented for GSI-191. An Applied Flow Technology (AFT) Fathom 6.0 ECCS flow model is used to determine the effects on the RHR pump NPSH of the new sump strainer and screen head loss values have when in the Cold Recirculation and Hot Recirculation modes. The Applied Flow Technology (AFT) Fathom 6.0 software has been verified for safety-related use by calculation ARC-587. Fathom is a fluid dynamic simulation software to calculate pressure drop and pipe flow distribution in liquid and low-velocity gas piping and ducting systems.

### **NPSH Calculation Summary**

The results of the NPSH calculations for the RHR pumps during the cold leg and hot leg recirculation mode of operate are summarized as follows.

1. The AFT Fathom 6.0 ECCS flow model from ARC-684, Rev. 0, was used to determine the effects of various sump water levels and temperatures on the RHR pump flow rate and NPSH with the new sump strainer and screen head loss values for both the Cold Recirculation and Hot Recirculation modes. Twelve different scenarios were investigated as shown in Table 3. The results of the Fathom runs for each scenario are shown in Table 4. The limiting margin condition of NPSH for the RHR pumps is the scenario based upon the minimum water level (1'10") in the containment sump during cold leg recirculation prior to swap over of the containment spray (CS) pumps. The results of the computer model show the RHR-B pump (PEJ01B) margin after adjustment for Containment Sump Strainers loss is 4.67 ft at a pump flow rate of 4627 gpm. The results of the computer model show the limiting RHR-A pump (PEJ01A) margin after Containment Sump Strainers adjustment is 5.44 ft at a pump flow rate of 4564 gpm. The Containment Sump Strainers adjustment subtracts the containment sump strainer head loss from the NPSH margin determined from the computer model. This was done in lieu of a variable resistance added to the model the containment sump head loss as a variable resistance may be non-conservative (Ref. CARS 200802526).
2. Previous revisions of EJ-29 utilized 4800 gpm as the limiting flowrate for the RHR pump in the recirculation mode of operation. This flowrate is also reflected in FSAR Table 6.2.2-7. As indicated by the results in Table 4, the Fathom model predicts the RHR pump flow rates during the cold leg recirculation and hot leg recirculation modes of operation is limited to a value less than 4800 gpm due to the hydraulic resistance in the piping system. Since the NPSH margin has been historically documented at 4800 gpm for Callaway, the FATHOM model had to be manipulated such that the discharge piping was removed in order to achieve flow pump rates of 4800 gpm with pump suction from the containment sump. The results of these Fathom runs are shown in Table 5. The limiting NPSH margin after adjusting for sump strainers is 4.13 feet for Pump A (decreased from 5.44 ft at a pump flow rate of 4564 gpm) and 3.70 feet for pump B (decreased from 4.67 ft at a pump flow rate of 4627 gpm) with an RHR pump flow rate of 4800 gpm. Therefore, adequate NPSH margin exists at the historical condition in the FSAR.
3. Fathom runs were also performed to identify the flow rate at which  $NPSHA = NPSHR$  for the RHR pumps. Table 6 shows that  $NPSHA = NPSHR = 26.10$  feet for pump A at 4893 gpm with a sump water level of 2002' 4' and a sump fluid temperature of 211.9°F and that  $NPSHA = NPSHR = 26.22$  feet for pump B at 4815 gpm with a sump water level of 2002' 4' and a sump fluid temperature of 211.9°F. The FATHOM model had to be manipulated such that the discharge piping was removed to achieve the limiting flow rates when  $NPSHA = NPSHR$ . For both the A and B pumps the limiting flow rate is greater than the historical value of 4800 gpm.
4. Two sensitivities were also performed using Fathom to determine the NPSH available from the containment sump at RHR pump flowrates of 4900 gpm and 5000 gpm. The FATHOM model had to be manipulated such that the discharge piping was removed to achieve flow rates greater than 4800 gpm. Since the containment recirculation sump strainer head loss is based on an RHR flowrate of 4880 gpm, the head loss values were conservatively rounded up to 0.5 ft (corresponding to 0.307 ft) and 1 ft. (corresponding to 0.749 ft). Table 7 shows the results of these Fathom runs which shows the limiting margin condition of NPSH of the RHR pumps is with the minimum water level (1'10") in containment sump during cold leg recirculation prior to swap over of the containment

spray (CS) pumps. The results of the computer model show the RHR-B pump (PEJ01B) margin after adjustment for Containment Sump Strainers at 4900 gpm and 5000 gpm are 2.95 ft and 2.38 ft, respectively. The results of the computer model show the RHR-A pump (PEJ01A) margin after adjustment for Containment Sump Strainers at 4900 gpm and 5000 gpm are 3.39 ft and 2.82 ft, respectively. The conclusion of this calculation sensitivity shows that the acceptance criteria is met since NPSHa exceeds NPSH required.

5. The calculations also contain a sensitivity study to determine the impact of a two percent over speed of the ECCS pumps due to the assumption of a steady state 2% frequency increase per Technical Specification 3.8.1 (2 percent over frequency). Table 8 shows the affinity laws used in Fathom to adjust pump performance due to speed increases. It is noted that flow rate and pump efficiency are assumed to vary linearly with speed, pump developed head and required NPSH are assumed to vary with the square of the speed, and pump power is assumed to vary to the cube of the speed. The Fathom results are summarized in Table 9. The conclusion of the calculation shows the limiting margin condition of NPSH for 2% over speed of the RHR pumps is the scenario based upon the minimum water level (1'10") in containment sump during cold leg recirculation prior to swap over of the containment spray (CS) pumps. The results of the computer model show the RHR-B pump (PEJ01B) margin after Containment Sump Strainers for two percent over speed is 3.67 ft at a flow rate of 4724 gpm. This compares with the base margin of 4.67 ft at a pump flow rate of 4627 gpm. The required NPSH increased from 29.05 feet at 4627 gpm to 29.9 feet at 4724 gpm due to both the higher flow rate and increased impeller speed.

It is noted that the impact of the 2% frequency change was evaluated using the pump affinity laws and not according to the WCAP-17308-NP-A method. While these results confirm that a 2% change in frequency yields acceptable NPSH margin, a more direct approach which is consistent both with the WCAP-17308-NP-A method and the magnitude of the frequency and voltage changes implemented by Callaway is included.

### **NPSH Impact of Speed Increases using Pre-Operational Test Data**

The NPSH margins for the various scenarios summarized above are based on flow rates and head losses calculated using the AFT Fathom software. It is noted that the use of standard friction data and component hydraulic loss factors is conservative for NPSH calculation since the published loss coefficients are conservative and will result in higher head losses and lower available NPSH. However, since most of the hydraulic resistance is on the discharge side of the pump, this also implies that calculated flow rates for systems may be lower than the actual flow rates. This is especially true in a system where the majority of hydraulic resistance is due to non-adjustable head losses, such as frictional losses due to piping and hydraulic losses due elbows, flow area changes and other fittings and components which cannot be throttled. To preclude excessive pump runout flow rate and insufficient NPSH for emergency core cooling pumps, pre-operational testing is used to confirm that maximum pump runout flow rates and NPSH limits are met. When the pre-operational testing for the Callaway RHR pumps was completed in 1983, flow restriction orifices were added to the cold leg recirculation and hot leg recirculation flow paths to restrict the runout flow rate within acceptable NPSH limits.

It was not practical to perform pre-operational testing of the RHR pumps with suction from the containment sumps. Also, since the RHR system is sensitive to variations in water level between the RWST and RCS, pre-operational testing of the RHR post-accident recirculation modes of operation was performed with RHR pump suction from the RCS hot legs in order to preclude water level changes during the test. The test acceptance criteria were developed in terms of allowable RHR pump flow rate as a function of RHR pump suction pressure to address the fact that the suction flow path from the containment sumps was not used during testing. Since the RHR pump discharge path to the RCS and RHR pump supply path to the CCPs and SIPs is aligned correctly and in use during the test, acceptable RHR pump runout flow rate is verified by limiting the pump flow rate to its maximum allowable NPSH flow when the pump suction pressure equals the calculated suction pressure during limiting NPSH conditions.

Table 11 provides the pre-operational test data collected as part of CS-03EJ03, which is the RHR emergency core cooling test criteria. Table 12 provides the pre-operational test data collected as part of CS-02EM02, which is the CCP and SIP flow balancing test criteria. The data from Table 11 and Table 12 is compiled in Table 13 and calculations are performed to estimate the RHR pump suction flow from the sump after accounting for pump speed increases associated with voltage and frequency variations. The data in the first six rows for RHR pump A and B in Table 13 are based on the data in Table 11 from the RHR pre-operational test CS-03EJ03. These tests were performed on September 13-14, 1983. The data in the next twelve rows for CCA, CCB, SIA and SIB is from the CS-03EM02 flow balance testing conducted on August 7, 1983. The following twelve rows present the results of basic calculations. The  $\Delta P$  for each pump is simply the discharge pressure minus the suction pressure. The RHR flow is the RHR pump flow minus the CCA, CCB, SIA and SIB flows and represents the flow delivered directly to the RCS by the RHR pump. The resistance is the pump  $\Delta P$  divided by flow squared. The same calculations are performed for the CC and SI pumps. As noted in the Cold Leg recirculation mode the CCP and SIP are headered together, and the pump  $\Delta P$  is the average of the individual pump values. For the hot leg recirculation mode, each SIP is treated separately.

LTR-SEE-18-228, Rev. 2, implemented WCAP-17308-NP-A on Callaway and is used to determine the change in pump head associated with speed changes due to voltage and frequency variations. For the RHR pumps, Table 5-20 of LTR-SEE-18-228 Rev. 2 has a maximum pump head change of 6.3 feet due to speed changes. This corresponds to 2.72 psi which is then added to the RHR pump  $\Delta P$ . The RHR flow to the RCS is the square root of the pump developed pressure divided by the resistance. For the CCP pumps, Table 5-35 of LTR-SEE-18-228 Rev. 2 has a maximum pump head change of 93.6 feet due to speed changes. This corresponds to 40.43 psi which is then added to the CCP pump  $\Delta P$ . The CCP flow to the RCS is the square root of the pump developed pressure divided by the resistance. For the SIP pumps, Table 5-39 of LTR-SEE-18-228 Rev. 2 has a maximum pump head change of 49.1 feet due to speed changes. This corresponds to 21.21 psi which is then added to the SIP pump  $\Delta P$ . The SIP flow to the RCS is the square root of the pump developed pressure divided by the resistance.

As a result of these adjustments to incorporate the effect of speed changes on RHR pump flow, the RHR pump A cold leg recirculation flow rate increases from 4665 gpm to 4712 gpm. The RHR pump B cold leg recirculation flow rate increases from 4665 gpm to 4725 gpm. The RHR pump A hot leg recirculation flow rate increases from 4718 gpm to 4774 gpm. The RHR pump B hot leg recirculation flow rate increases from 4759 gpm to 4814 gpm.

The RHR pump B hot leg recirculation flow rate at increased pump speed is 4814.4 gpm, which is slightly greater than the historical NPSH flow limit of 4800 gpm. The available NPSH for pump B from Table 5 changes as follows. Table 3 indicates the sump water level used in Table 5 for cold leg recirculation is 2002'-4". Therefore, the head loss using a pump elevation of 1972.07 feet is 4.02 feet. The head loss increases by the square of the flow and increases from 4.02 feet to 4.05 feet at 4814.4 gpm. The available NPSH is  $2002.33 \text{ ft} - 1972.07 \text{ ft} - 4.05 \text{ ft} = 26.22 \text{ feet}$ . Table 8 demonstrates the reduction in NPSH margin associated with the increase in NPSHR. Table 5 indicates the required NPSH for pump B is 21.73 at 4800 gpm and Table 7 indicated the required NPSH for pump B is 22.12 feet at 4900 gpm. At 4814.4 gpm, the required NPSH is 21.79 feet by linear interpolation. LTR-SEE-18-228, Rev. 2) indicates the RHR pump speed changes by 13.15 rpm from 1784 rpm to 1797.15 rpm. This increases the required NPSH from 21.79 feet to 22.11 feet. The NPSH margin for RHR pump A decreases from 4.13 feet to 3.81 feet and the NPSH margin for RHR pump B is  $\text{NPSHA} - \text{NPSHR} = 26.22 \text{ ft} - 22.11 \text{ ft} = 4.11 \text{ feet}$ . The conclusion of the calculation shows that the acceptance criteria are met since NPSH available exceeds NPSH required with sufficient margin.

Table 3 Scenarios of Sump Water Level, Fluid Temperature, Pumps and Configuration					
	Scenario Description	Pump	Sump Level (ft)*	Fluid Temp (°F)**	Scenario Basis
A	RHR A, Cold Leg Recirculation	PEJ01A	2001'10"	211.9	The minimum water level (1'10") during cold leg recirculation prior to swap over of the containment spray (CS) pumps. The strainer head loss is based on only the "A" RHR pump drawing from the sump.
B	RHR A, Cold Leg Recirculation with Containment Spray Pumps (CSP)	PEJ01A, PEN01A	2002'4"	211.9	The minimum water level after swap over of the "A" CS pumps to the suction from the containment sumps during cold leg recirculation. The strainer head loss is based on the "A" RHR and CS pumps drawing from sump.
C	RHR A, Cold Leg Recirculation with CSP	PEJ01A, PEN01A	2002'4"	200	These scenarios are based on the same assumptions as those for Scenario B discussed above with the exception of varying containment sump fluid temperatures. These scenarios reveal the sensitivity of several lower containment sump temperatures on NPSH margin. The containment water level used is the same as the CS swap over and consistent with the minimum long term containment water level from M-FL- 18, Add 6.
D	RHR A, Cold Leg Recirculation with CSP	PEJ01A, PEN01A	2002'4"	175	
E	RHR A, Cold Leg Recirculation with CSP	PEJ01A, PEN01A	2002'4"	150	
F	RHR B, Cold Leg Recirculation	PEJ01B	2001'10"	211.9	These scenarios are the same as those from Scenarios A - E with the exception that the "B" train is analyzed in lieu of the "A" train.
G	RHR B, Cold Leg Recirculation with CSP	PEJ01B, PEN01B	2002'4"	211.9	
H	RHR B, Cold Leg Recirculation with CSP	PEJ01B, PEN01B	2002'4"	200	
I	RHR B, Cold Leg Recirculation with CSP	PEJ01B, PEN01B	2002'4"	175	
J	RHR B, Cold Leg Recirculation with CSP	PEJ01B, PEN01B	2002'4"	150	
K	RHR A, Hot Leg Recirculation	PEJ01A	2002'4"	150	This scenario is applicable to the "A" train hot leg recirculation mode of operation. The strainer head loss is based on the "A" RHR and CS pumps drawing from the containment recirculation sump at the head loss value corresponding to the 30 day value from Ref. 4.
L	RHR B, Hot Leg Recirculation	PEJ01B	2002'4"	150	This scenario is similar to Scenario K with the exception that the "B" train is analyzed in lieu of the "A" train

Table 4 NPSH Results for Postulated Scenarios of Sump Water Level, Fluid Temperature, Pumps and Configuration							
ARC 687, Rev. 1, Attachment #*	Scenario Description*	Pump Flow (gpm)	NPSH Avail. (ft)*	NPSH Req. (ft)*	Margin (ft)*	FEN01A/B Total Head Loss (ft)**	Margin after sumps (ft)
2	RHR A, Cold Leg Recirculation	4564	26.14	20.39	5.75	0.307	5.44
3	RHR A, Cold Leg Recirculation with CSP	4566	26.63	20.4	6.23	0.749	5.48
4	RHR A, Cold Leg Recirculation with CSP	4556	34.17	20.37	13.80	0.828	12.97
5	RHR A, Cold Leg Recirculation with CSP	4537	45.53	20.3	25.23	0.828	24.40
6	RHR A, Cold Leg Recirculation with CSP	4521	52.44	20.23	32.21	0.828	31.38
7	RHR B, Cold Leg Recirculation	4627	26.03	21.05	4.98	0.307	4.67
8	RHR B, Cold Leg Recirculation with CSP	4629	26.52	21.06	5.46	0.749	4.71
9	RHR B, Cold Leg Recirculation with CSP	4619	34.06	21.02	13.04	0.828	12.21
10	RHR B, Cold Leg Recirculation with CSP	4600	45.42	20.95	24.47	0.828	23.64
11	RHR B, Cold Leg Recirculation with CSP	4583	52.33	20.88	31.45	0.828	30.62
12	RHR A, Hot Leg Recirculation	4529	52.42	20.26	32.16	1.439	30.72
13	RHR B, Hot Leg Recirculation	4606	52.29	20.97	31.32	1.439	29.88
*ARC-687, Rev. 1							

Table 5 NPSH Results at RHR Sump flow rate of 4800 gpm							
Attachment #	Scenario Description	Flow (gpm)	NPSHAvail. (ft)	NPSHReq. (ft)*	Margin (ft)	FEN01 Total Head Loss (ft)	Margins after sumps (ft)
3	RHR A, Cold Leg Recirc	4800	25.75	21.31	4.44	0.307	4.13
3	RHR B, Cold Leg Recirc	4800	25.74	21.73	4.01	0.307	3.70
4	RHR A, Cold Leg Recirc + CSS	4800	26.25	21.31	4.94	0.749	4.19
4	RHR B, Cold Leg Recirc + CSS	4800	26.24	21.73	4.51	0.749	3.76

\* Note that the differences in NPSHr at the same flowrates can be attributed to the differences in pump speed.

*Table 6 Sensitivity for Pump flow so NPSHa = NPSHr:										
Scenario Description	Attach. Number & page	Pump	Flow (gpm)	Sump Level (ft)	Sump Temp (OF)	NPSH Avail. (ft)	NPS H Req. (ft)	Margin (ft)	FEN01 Head Loss (ft)	Margin after sumps (ft)
RHR A, Margin=4.430 ft	14, pg 5	PEJOIA	4893	2002'4"	211.9	26.10	21.67	4.430	4.430	0.000
RHR B, Margin=4.430 ft	15, pg 5	PEJOIB	4815	2002'4"	211.9	26.22	21.79	4.430	4.430	0.000

Table 7 Sensitivity of NPSH margin to RHR pump flows of 4900 gpm and 5000 gpm								
Appendix B Attachment	Scenario Description*	Flow (gpm)*	Sump Temp (Deg. F)*	NPSHA. (ft)*	NPSHR (ft)*	Margin (ft)*	FEN01 Total Head Loss (ft)****	Margins after sumps (ft)
2	RHR A, Cold Leg Recirc	4900	211.9	25.59	21.7	3.89	0.5	3.39
2	RHR B, Cold Leg Recirc	4900	211.9	25.57	22.12	3.45	0.5	2.95
3	RHR A, Cold Leg Recirc + CSS	4900	211.9	26.09	21.7	4.39	1	3.39
3	RHR B, Cold Leg Recirc + CSS	4900	211.9	26.07	22.12	3.95	1	2.95
4	RHR A, Cold Leg Recirc	5000	211.9	25.42	22.1	3.32	0.5	2.82
4	RHR B, Cold Leg Recirc	5000	211.9	25.4	22.52	2.88	0.5	2.38
5	RHR A, Cold Leg Recirc + CSS	5000	211.9	25.92	22.1	3.82	1	2.82
5	RHR B, Cold Leg Recirc + CSS	5000	211.9	25.9	22.52	3.38	1	2.38

Table 8 Affinity Laws Used by AFT FATHOM				
Parameter	Units	Symbol	Affinity Law	New Parameter Value
Speed	rpm	N	<i>Speed Ratio</i> , $S = \frac{N_1}{N_2}$	$N_2 = \frac{N_1}{S}$
Flow	Gpm or lb/min	Q	<i>Flow Ratio</i> , $\frac{Q_1}{Q_2} = S = \frac{N_1}{N_2}$	$Q_2 = \frac{Q_1}{S}$
Developed Head	feet	$\Delta H$	<i>Head Ratio</i> , $\frac{\Delta H_1}{\Delta H_2} = S^2 = \left(\frac{N_1}{N_2}\right)^2$	$\Delta H_2 = \frac{\Delta H_1}{S^2}$
NPSH	feet	NPSH	<i>NPSH Ratio</i> , $\frac{NPSHR_1}{NPSHR_2} = S^2 = \left(\frac{N_1}{N_2}\right)^2$	$NPSHR_2 = \frac{NPSHR_1}{S^2}$
Power	horsepower	P, HP	<i>Power Ratio</i> , $\frac{P_1}{P_2} = S^3 = \left(\frac{N_1}{N_2}\right)^3$	$P_2 = \frac{P_1}{S^3}$
Efficiency		$\eta$	<i>Efficiency Ratio</i> , $\frac{\eta_1}{\eta_2} = S = \frac{N_1}{N_2}$	$\eta_2 = \frac{\eta_1}{S}$

Table 9 Scenarios with 2% speed increase due to frequency variation								
Attachment*	Scenario Description	RHR Pump*Speed	Sump Temp (ft)*	NPSH Avail. (ft)*	NPSH Req. (ft)*	Margin (ft)*	FEN01 Total Head Loss (ft)****	Margins after sumps (ft)
2	RHR A, Cold Leg Recirculation	102.5	211.9	25.99	21.22	4.77	0.307	4.46
3	RHR A, Cold Leg Recirculation with CSP	102.5	211.9	26.48	21.23	5.25	0.749	4.50
4	RHR A, Cold Leg Recirculation with CSP	102.5	200	34.02	21.19	12.83	0.828	12.00
5	RHR A, Cold Leg Recirculation with CSP	102.5	175	45.38	21.12	4.26	0.828	23.43
6	RHR A, Cold Leg Recirculation with CSP	102.5	150	52.29	21.06	31.23	0.828	30.40
7	RHR B, Cold Leg Recirculation	104.3	211.9	25.88	21.9	3.98	0.307	3.67
8	RHR B, Cold Leg Recirculation with CSP	104.3	211.9	26.37	21.9	4.47	0.749	3.72
9	RHR B, Cold Leg Recirculation with CSP	104.3	200	33.91	21.86	12.05	0.828	11.22
10	RHR B, Cold Leg Recirculation with CSP	104.3	175	45.27	21.79	23.48	0.828	22.65
11	RHR B, Cold Leg Recirculation with CSP	104.3	150	52.18	21.72	30.46	0.828	29.63
12	RHR A, Hot Leg Recirculation	102.5	150	52.28	21.09	31.19	1.439	29.75
13	RHR B, Hot Leg Recirculation	104.3	150	52.14	21.81	30.33	1.439	28.89

Scenario Description*	(+0% pump speed)					(+2% pump speed)*				
	Pump Flow (gpm)	NPSH Avail. (ft)*	NPSH Req. (ft)*	Margin (ft)*	Margin after sumps (ft)	Flow (gpm) (+2% pump speed)*	NPSH Avail. (ft)*	NPSH Req. (ft)*	Margin (ft)*	Margin after sumps (ft)
RHR A, CLR	4564	26.14	20.39	5.75	5.44	4657	25.99	21.22	4.77	4.46
RHR A, CLR with CSP	4566	26.63	20.4	6.23	5.48	4658.9	26.48	21.23	5.25	4.50
RHR A, CLR with CSP	4556	34.17	20.37	13.80	12.97	4649.2	34.02	21.19	12.83	12.00
RHR A, CLR with CSP	4537	45.53	20.3	25.23	24.40	4630.2	45.38	21.12	24.26	23.43
RHR A, CLR with CSP	4521	52.44	20.23	32.21	31.38	4613.4	52.29	21.06	31.23	30.40
RHR B, CLR	4627	26.03	21.05	4.98	4.67	4720.1	25.88	21.9	3.98	3.67
RHR B, CLR with CSP	4629	26.52	21.06	5.46	4.71	4721.9	26.37	21.9	4.47	3.72
RHR B, CLR with CSP	4619	34.06	21.02	13.04	12.21	4712	33.91	21.86	12.05	11.22
RHR B, CLR with CSP	4600	45.42	20.95	24.47	23.64	4692.6	45.27	21.79	23.48	22.65
RHR B, CLR with CSP	4583	52.33	20.88	31.45	30.62	4675.4	52.18	21.72	30.46	29.63
RHR A, HLR	4529	52.42	20.26	32.16	30.72	4621.1	52.28	21.09	31.19	29.75

Step	$\Delta H$ (inch H <sub>2</sub> O)	Suction Pressure (psig)	Discharge Pressure (psig)	Temp. (°F)	Flow Coefficient	RHR Flow (gpm)
7.3.8 Cold Leg Injection Pump A	498	12.0	148	77	222.36	4962
7.4.8 Cold Leg Injection Pump B	492	12.2	154	71.6	222.37	4932
7.5.32 Cold Leg Recirculation Pump A	440	11.7	157	68	222.37	4665
7.7.32 Hot Leg Recirculation Pump A	450	11.6	155	68	222.37	4718
7.6.33 Cold Leg Recirculation Pump B	440	11.2	158	75	222.37	4665
7.8.32 Hot Leg Recirculation Pump B	458	10.8	156	77	222.36	4759

Table 12 CS-02EM02 Data Sheet 8.14 RHR Recirculation Performance					
	Lineup	CLR	CLR	HLR	HLR
Pump	Procedure step	7.9.12`	7.9.34	7.9.41	7.9.19
RHRA	Suction pressure (psi)	8			8.2
	Discharge pressure (psi)	144			144
	Pump Flow (gpm)	4691			4996.9
	Orifice Δh (inwc)	445			495
	Temp (°F)	87			90
RHRB	Suction pressure (psi)		8.5	8.5	
	Discharge pressure (psi)		148	139	
	Pump Flow (gpm)		4987	4972	
	Orifice Δh (inwc)		493	500	
	Temp (°F)		85	95	
CCA	Suction pressure (psi)	108.7	98	99.5	107
	Discharge pressure (psi)	1480	1490	1460	1480
	Pump Flow (gpm)	425	420	420	420
CCB	Suction pressure (psi)	108	98	92	106
	Discharge pressure (psi)	1510	1530	1520	1510
	Pump Flow (gpm)	345	350	350	345
SIA	Suction pressure (psi)	107.5	100	82	101
	Discharge pressure (psi)	1325	1260	750	760
	Pump Flow (gpm)	420	418	655	650
SIB	Suction pressure (psi)	106.2	112	96.5	99
	Discharge pressure (psi)	1320	1320	850	845
	Pump Flow (gpm)	425	430	655	645
	Actual RHR Supply to CC/SI	1615	1618	2080	2060
	Assumed RHR Supply to CC/SI	1800	1800	2200	2200

Table 13 Frequency and Voltage Change on RHR Sump Flow						
	Lineup	UNITS	A CLR	B CLR	B HLR	A HLR
Pump	Procedure step		7.9.12`	7.9.34	7.9.41	7.9.19
RHRA	Suction pressure	(psi)	11.7			11.6
	Discharge pressure	(psi)	157			155
	Pump Flow	(gpm)	4665			4718
RHRB	Suction pressure	(psi)		11.2	10.8	
	Discharge pressure	(psi)		158	156	
	Pump Flow	(gpm)		4665	4759	
CCA	Suction pressure	(psi)	108.7	98	79.5	107
	Discharge pressure	(psi)	1480	1490	1460	1480
	Pump Flow	(gpm)	425	420	420	420
CCB	Suction pressure	(psi)	108	98	92	106
	Discharge pressure	(psi)	1510	1530	1520	1510
	Pump Flow	(gpm)	345	350	350	345
SIA	Suction pressure	(psi)	107.5	100	82	101
	Discharge pressure	(psi)	1325	1260	750	760
	Pump Flow	(gpm)	420	418	655	650
SIB	Suction pressure	(psi)	106.2	112	96.5	99
	Discharge pressure	(psi)	1320	1320	850	845
	Pump Flow	(gpm)	425	430	655	645
	Ps		11.7	11.2	10.8	11.6
	RHR ΔP		145.3	146.8	145.2	143.4
	RHR flow to RCS		3050	3047	2679	2658
	RHR Resistance	(psi/gpm <sup>2</sup> )	1.56195E-05	1.58118E-05	2.0231E-05	2.02973E-05
	CCP ΔP	(psi)	1386.65	1412	1404.25	1388.5

	CCP flow to RCS	(gpm)	770	770	770	765
	CCP Resistance	(psi/gpm <sup>2</sup> )	0.002338759	0.002381515	0.00236844	0.002372592
	SIP ΔP	(psi)	1215.65	1184	710.75	659
	SIP flow to RCS	(gpm)	845	848	1310	650
	SIP Resistance	(psi/gpm <sup>2</sup> )	0.001702531	0.001646493	0.000414166	0.001559763
	SIP ΔP	(psi)				746
	SIP flow to RCS	(gpm)				645
	SIP Resistance	(psi/gpm <sup>2</sup> )				0.001793161
	RHR ΔPf	(psi)	2.72	2.72	2.72	2.72
	RHR ΔPT	(psi)	148.02	149.52	147.92	146.12
	RHR Q	(gpm)	3078.43	3075.11	2703.99	2683.10
	RHR ΔQ	(gpm)	28.43	28.11	24.99	25.10
	CCP ΔPf	(psi)	40.43	40.43	40.43	40.43
	CCP ΔPT	(psi)	1427.08	1452.43	1444.68	1428.93
	CCP Q	(gpm)	781.15	780.95	781.01	776.06
	CCP ΔQ	(gpm)	11.15	10.95	11.01	11.06
	SIP ΔPf	(psi)	21.21	21.21	21.21	21.21
	SIP ΔPT	(psi)	1236.86	1205.21	731.96	680.21
	SIP Q	(gpm)	852.34	855.56	1329.40	660.38
	SIP ΔQ	(gpm)	7.34	7.56	19.40	10.38
	SIP ΔPf	(psi)				21.21
	SIP ΔPT	(psi)				767.21
	SIP Q	(gpm)				654.10
	SIP ΔQ	(gpm)				9.10
	RHR ΔQ Total	(gpm)	46.91	46.62	55.40	55.64
	RHR Q Total	(gpm)	4711.91	4711.62	4814.40	4773.64

Table 14 Frequency and Voltage Change on RHR NPSH			
RHR Pump		A	B
Speed	rpm	1784	1784
Speed increase	rpm	13.14	13.14
% Increase		0.74	0.74
NPSHR at 4800 gpm at nominal speed	feet	21.31	22.73
NPSHR at 4800 gpm at increased speed	feet	21.63	23.07
NPSH margin at nominal speed	feet	4.13	4.70
NPSH margin at increased speed	feet	3.81	4.36

***COLD LEG RECIRC MODE***

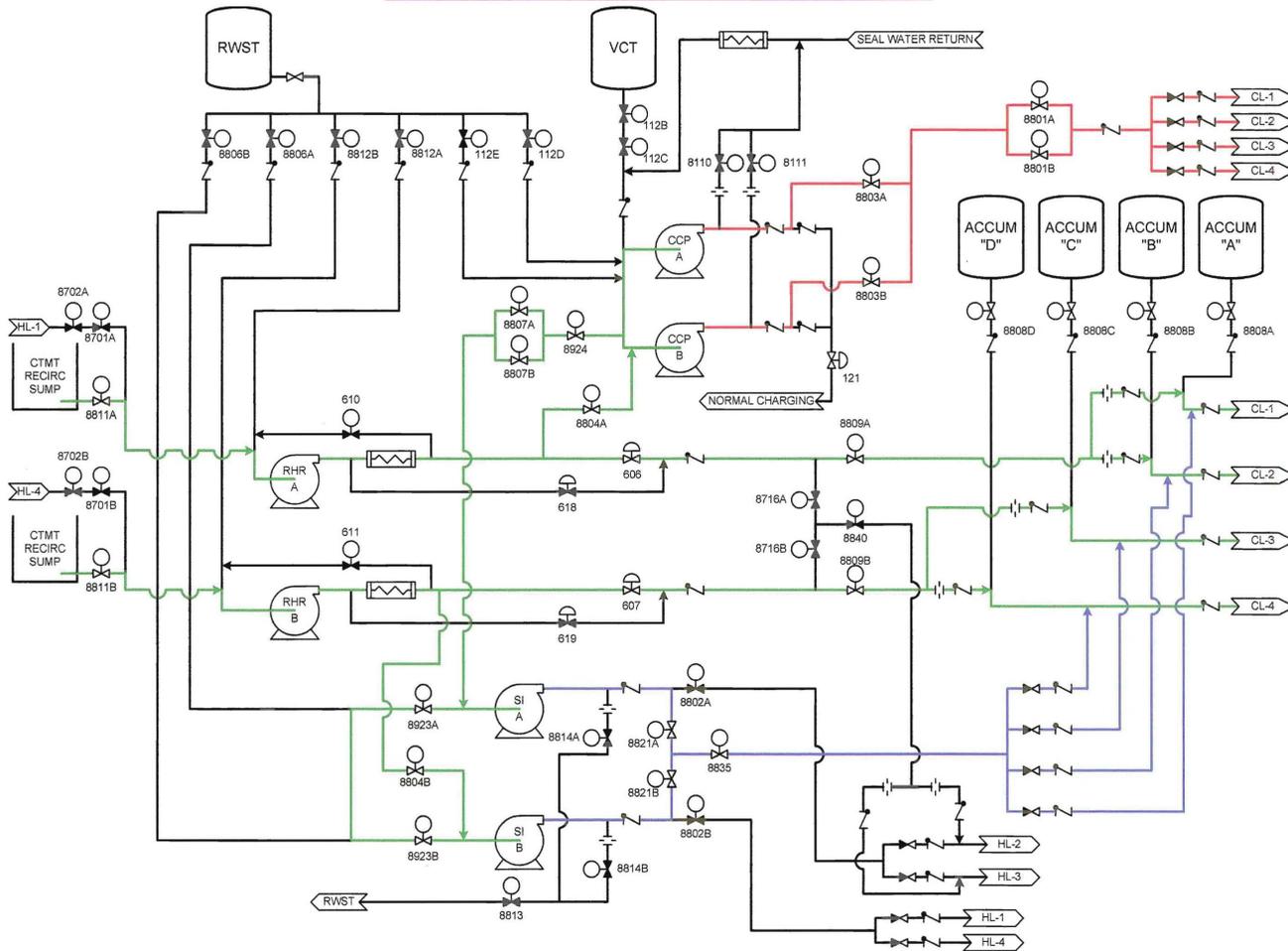


Figure 1 Callaway Cold Leg Recirculation Operating Mode

### **HOT LEG RECIRC MODE**

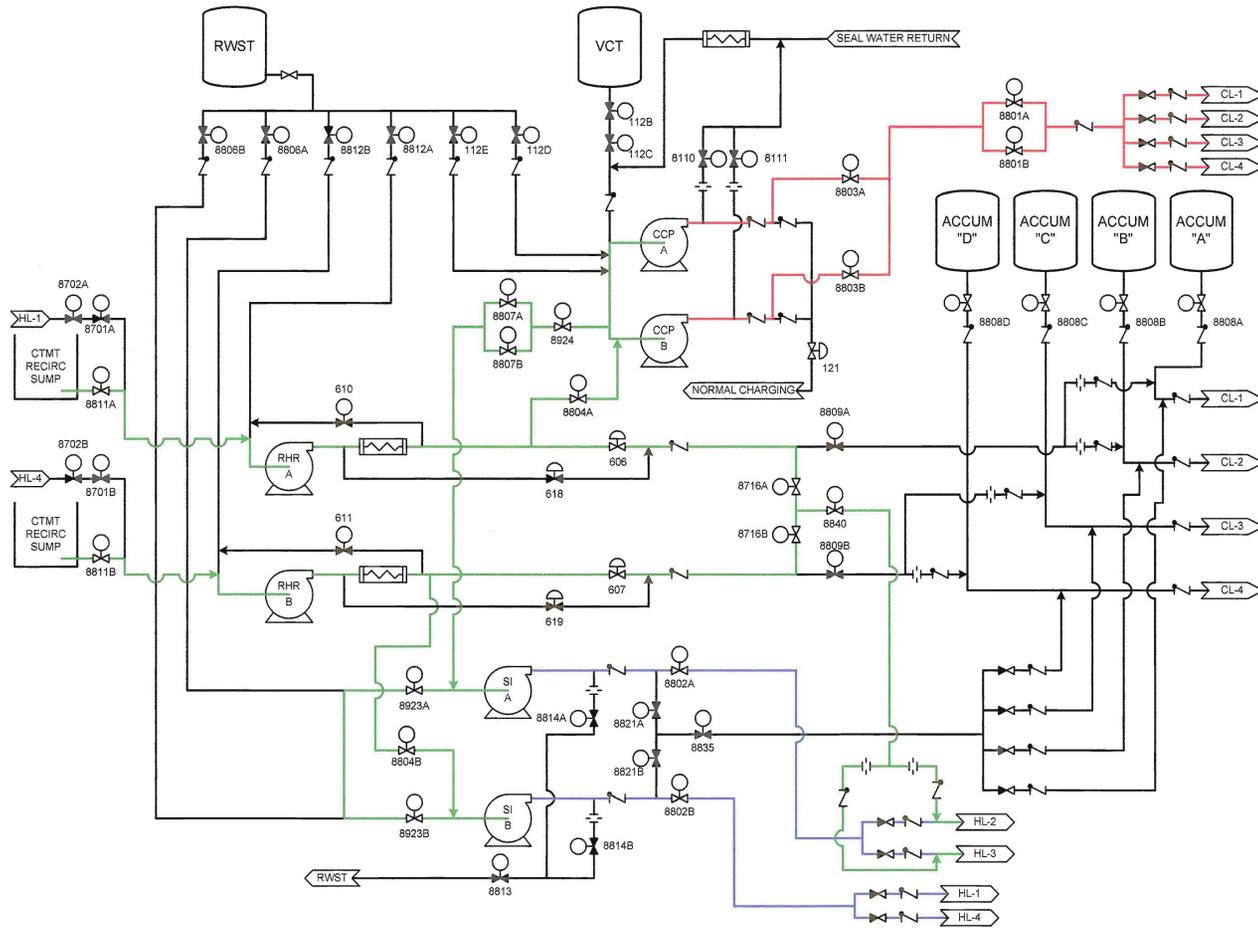


Figure 2 Callaway Hot Leg Recirculation Operating Mode