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DCP/NRC0598
Docket No.: STN-52-003

September 5, 1996

Document Control Desk
U.S. Nuclear Regulatory Commission
Washington, D.C. 20555

ATTENTION: T. R. QUAY

SUBJECT: AP600 LOFTRAN COMPUTER CODE ISSUE RESOLUTION

Dear Mr. Quay:

The attachment to this letter provides responses to NRC Supplemental Draft Safety Evaluation Report (SDSER) open items related to the LOFTRAN computer code and its application to AP600 safety analyses. The SDSER open items addressed in this letter are 21.6.1.4-1, 21.6.1.6-1, 21.6.1.7-1, 21.6.1.7-2, 21.6.1.7-3, 21.6.1.7-4, 21.6.1.7-5, 21.6.1.7-6, 21.6.1.7-7, 21.5.4-1, 21.5.4-2 and 21.5.4-3.

Table 1 identifies the current Westinghouse status of LOFTRAN open items. We request NRC staff review of the attached information.

Please contact John C. Butler on (412) 374-5268 if you have any questions concerning this transmittal.

Brian A. McIntyre, Manager
Advanced Plant Safety and Licensing

/nja

Attachment

cc: T. Kenyon, NRC (w/o Enclosures/Attachments)
W. Huffman, NRC
R. Landry, NRC
N. J. Liparulo, Westinghouse (w/o Enclosures/Attachments)

E001/,

2909A

Table 1

SDSER Open Item	Westinghouse Status	Comments
21.6.1.4-1	Closed	
21.6.1.6-1	Action W	SSAR Chapter 15 revision necessary to fully address.
21.6.1.7-1	Closed	
21.6.1.7-2	Action W	WCAP-14307 and WCAP-14234 will be revised to incorporate information from RAI responses.
21.6.1.7-3	Closed	
21.6.1.7-4	Closed	
21.6.1.7-5	Closed	
21.6.1.7-6	Closed	
21.6.1.7-7	Closed	
21.5.4-1	Closed	
21.5.4-2	Closed	
21.5.4-3	Closed	
21.6.1.6-1	Action W	PRHR Test Report revision necessary to fully address.

SDSER Open Item 21.6.1.4-1

Westinghouse needs to submit responses to RAIs on the adequacy of the analytical models in the LOFTRAN code for application to the AP600 passive reactor design.

SDSER Open Item 21.6.1.7-1

Westinghouse needs to submit responses to RAIs on LOFTRAN.

Response:

Responses to requests for additional information (RAI) on the LOFTRAN computer code and its application to the AP600 have been submitted to the NRC. Table 1 identifies the LOFTRAN RAIs and the date of the Westinghouse letter containing the requested response.

Westinghouse Status: Closed

Table 1
Requests for Additional Information on the LOFTRAN Computer Code

RAI	Subject	Date of Response
440.263	WCAP-14234	03/01/96
440.264	WCAP-14234	01/31/96
440.265	WCAP-14234	01/31/96
440.266	WCAP-14234	03/01/96
440.267	WCAP-14234	01/19/96
440.268	WCAP-14234	03/01/96
440.269	WCAP-14234	05/13/96
440.270	WCAP-14234	01/19/96
440.271	WCAP-14234	05/13/96
440.272	WCAP-14234	05/13/96
440.273	WCAP-14234	05/13/96
440.274	WCAP-14234	05/13/96
440.275	WCAP-14234	05/13/96
440.276	WCAP-14234	05/13/96
440.277	WCAP-14234	05/13/96
440.278	WCAP-14234	01/31/96
440.279	WCAP-14234	01/31/96
440.280	WCAP-14234	01/29/96
440.281	WCAP-14234	11/17/95
440.282	WCAP-14234	01/12/96
440.283	WCAP-14234	11/17/95
440.284	WCAP-14234	01/04/96
440.285	WCAP-14234	01/29/96
440.286	WCAP-14234	01/12/96
440.287	WCAP-14234	01/04/96
440.288	WCAP-14234	01/31/96
440.289	WCAP-14234	01/31/96

RAI	Subject	Date of Response
440.290	WCAP-14234	01/29/96
440.291	WCAP-14234	01/12/96
440.292	WCAP-14234	11/17/95
440.293	WCAP-14234	11/17/95
440.294	WCAP-14234	11/17/95
440.295	WCAP-14234	11/17/95
440.296	WCAP-14234	11/17/95
440.297	WCAP-14234	11/17/95
440.298	WCAP-14234	11/17/95
440.299	WCAP-14234	01/26/96
440.300	WCAP-14234	01/04/96
440.301	WCAP-14234	01/04/96
440.302	WCAP-14234	01/29/96
440.303	WCAP-14234	11/17/95
440.304	WCAP-14234	11/17/95
440.305	WCAP-14234	01/12/96
440.306	WCAP-14234	12/15/95
440.307	WCAP-14234	05/13/96
440.308	WCAP-14234	01/19/96
440.309	WCAP-14234	05/13/96
440.310	WCAP-14234	05/13/96
440.311	WCAP-14234	01/04/96
440.312	WCAP-14234	12/21/95
440.313	WCAP-14234	11/17/95
440.314	WCAP-14234	01/29/96
440.315	WCAP-14234	01/04/96
440.316	WCAP-14234	01/04/96
440.317	WCAP-14234	11/17/95
440.318	WCAP-14234	11/17/95

RAI	Subject	Date of Response
440.319	WCAP-14234	11/17/95
440.320	WCAP-14234	01/19/96
440.321	WCAP-14234	01/19/96
440.322	WCAP-14234	01/26/96
440.323	WCAP-14234	01/26/96
440.324	WCAP-14234	05/13/96
440.447	LOFTRAN V&V	01/31/96
440.448	LOFTRAN V&V	01/19/96
440.449	LOFTRAN V&V	01/26/96
440.450	LOFTRAN V&V	01/31/96
440.451	LOFTRAN V&V	01/31/96
440.452	LOFTRAN V&V	01/31/96
440.453	LOFTRAN V&V	01/31/96
440.454	LOFTRAN V&V	01/31/96
440.455	LOFTRAN V&V	01/31/96
440.456	LOFTRAN V&V	01/31/96
440.457	LOFTRAN V&V	01/31/96
440.458	LOFTRAN V&V	01/31/96
440.459	LOFTRAN V&V	01/31/96
440.460	LOFTRAN V&V	01/29/96
440.461	LOFTRAN V&V	01/31/96
440.462	LOFTRAN V&V	01/31/96

SDSER Open Item 21.6.1.6-1

Westinghouse needs to describe, in Chapter 15 of the SSAR, the PRHR heat transfer option it has selected for each analysis in which LOFTRAN is applied and explain why the option is conservative for that application.

Response:

Chapter 15 of the SSAR will be revised to include the requested information.

Westinghouse Status: Action W

SDSER Open Item 21.6.1.7-2

Westinghouse needs to identify the information provided in RAI responses that will be incorporated into the LOFTRAN final verification and validation (V&V) document (WCAP-14307) or the code applicability document (WCAP-14234).

Response:

The responses to NRC RAIs on the LOFTRAN final V&V report (WCAP-14307) and the LOFTRAN code applicability document (WCAP-14234) will be incorporated in the reports as an Appendix and Revision 1 of these two reports will be issued.

Westinghouse Status: Action W

SDSER Open Item 21.6.1.7-3

Westinghouse needs to submit a detailed example of how it used auxiliary programs, hand calculations, and conservative assumptions to model pump trips and startups in LOFTRAN.

Respons :

The requested detailed example and explanation of the auxiliary codes used to support the LOFTRAN calculations is provided in the enclosed report. This report details the calculations of the RCS flow transients following a partial loss of flow event and a locked rotor or broken RCP shaft event.

Westinghouse Status: Closed

SDSER Open Item 21.6.1.7-4

Westinghouse needs to submit criteria for using the penalty model for CMT piping when "moderate" voiding takes place.

Response:

Boiling does not occur in the CMT during the design basis non-LOCA and steam generator tube rupture transients. Therefore, this model has not been used in the AP600 SSAR Chapter 15 analyses. The model generates warning messages to the user that boiling is occuring in the CMT or the cold balance line if the water subcooling in either location is less than a prescribed user input value. Flashing is assumed to occur if the following is true:

$$Tsat - T_{node\ i} < D_{cmt\ sat}$$

Where:

	Tsat	=	water saturation temperature at the CMT pressure
	$T_{node\ i}$	=	water temperature in the node i
	$D_{cmt\ sat}$	=	input subcooling limit & current limit = 5.0 °F

If this subcooling limit is exceeded, the effect of the potential steam accumulation at the CMT pipe top may be taken into account by a penalty on the cold leg to CMT balance line buoyancy calculation. Assuming that there is only steam in the vertical pipe portion at the CMT top, the density induced driving head that produces the recirculation flow is reduced by the following quantity:

$$Penalty = Hbub\ (\rho_{bal} - \rho_{steam})/144$$

Where:

	Hbub	=	Equivalent height of the stratified zone; is provided as input. A "realistic" value may be input or a very conservative calculation may be performed that uses an artificially large value that stops natural circulation as soon as boiling is detected.
	ρ_{bal}	=	mixture density in the cold leg to CMT balance line top node
	ρ_{steam}	=	saturation density at the CMT pressure

As noted above, none of the design basis non-LOCA and steam generator tube rupture analyses have produced boiling in the CMT or cold leg balance line. Of the non-LOCA events analyzed, the steam system piping failure (SSAR Section 15.1.5) is most likely to produce boiling. Should this occur, an artifically large Hbub penalty will be used for the core response analysis which would completely terminate CMT recirculation flow, thereby minimizing the amount of boron that reaches the core.

Westinghouse Status: Closed

SDSER Open Item 21.6.1.7-5

LOFTRAN should not be applied to any analysis involving actuation of the ADS because it has not been benchmarked against ADS actuation experiments.

Response:

Inadvertent depressurization of the RCS analyses are presented in Section 15.6.1 of the safety analysis reports. On previously licensed PWRs, inadvertent RCS depressurizations were postulated to occur due to opening of pressurizer relief or safety valves. While the reactor is at power, margin to departure from nucleate boiling (DNB) limits will be reduced as the RCS pressure decreases. Violation of DNB limits is precluded by tripping the reactor.

The RCS depressurization analyses performed with LOFTRAN and presented in Section 15.6.1 of safety analysis reports are short term analyses which demonstrate that the protection system will detect the depressurization and trip the reactor prior to violation of DNB limits. For this type of analysis, the most limiting transient is a one which will result in the most rapid rate of depressurization of the RCS.

The short term RCS depressurization analyses presented in section 15.6.1 of the AP600 SSAR have been expanded to include the inadvertent opening of ADS paths connected to the pressurizer. Analysis of these events are performed with LOFTRAN using assumptions which conservatively maximize the relief from the ADS path under consideration. This results in the maximum rate of RCS depressurization. No credit for ADS piping interactions or interactions with the IRWST which may reduce the rate of RCS depressurization is assumed in the analysis. In this analysis, benchmarking of the LOFTRAN ADS modeling against experiments is not needed because bounding ADS performance characteristics are used. This is the only analysis performed with LOFTRAN which involves the ADS.

LOFTRAN is not used for the simulation of any transients where ADS is used to mitigate the event or where simulation of the ADS piping and the IRWST interaction effects are important.

Westinghouse Status: Closed

SDSER Open Item 21.6.1.7-6

For each transient analyzed with LOFTRAN, Westinghouse needs to submit information on the impact of not conserving mass, energy, momentum, and volume.

Response:

Mass and energy balances were performed (using the methodology described in the response to RAI 440.288) to verify that the LOFTRAN/LOFTTR2 codes used for the AP600 non-LOCA and SGTR analyses conserve mass and energy with a reasonable degree of accuracy. Mass and energy balances were performed for a transient from each of the six main design basis accident sections of the SSAR where LOFTRAN is used. The results of these calculations are presented in Table 1, which shows that there is no appreciable mass or energy error developed for any of the LOFTRAN transients. Figures 1-6 present the transient mass and energy balances for the selected transients.

Table 1

SSAR Section	Transient Selected	Maximum Mass Error (%)	Maximum Energy Error (%)
Increase in Heat Removal From the Primary System	Steam System Piping Failure	-0.014 +0.035	-0.085 +0.066
Decrease in Heat Removal by the Secondary System	Loss of Normal Feedwater Flow	-0.007 +0.017	-0.012 +0.067
Decrease in Reactor Coolant System Flow Rate	Complete Loss of Forced Reactor Coolant Flow	-0.000 +0.000	-0.004 +0.013
Reactivity and Power Distribution Anomalies	Startup of an Inactive Reactor Coolant Loop at an Incorrect Temperature	-0.000 +0.000	-0.003 +0.007
Increase in Reactor Coolant Inventory	Chemical and Volume Control System Malfunction That Increases Reactor Coolant Inventory	-0.004 +0.004	-0.028 +0.078
Decrease in Reactor Coolant Inventory	Steam Generator Tube Rupture	-0.013 +0.010	-0.050 +0.108

Westinghouse Status: Closed

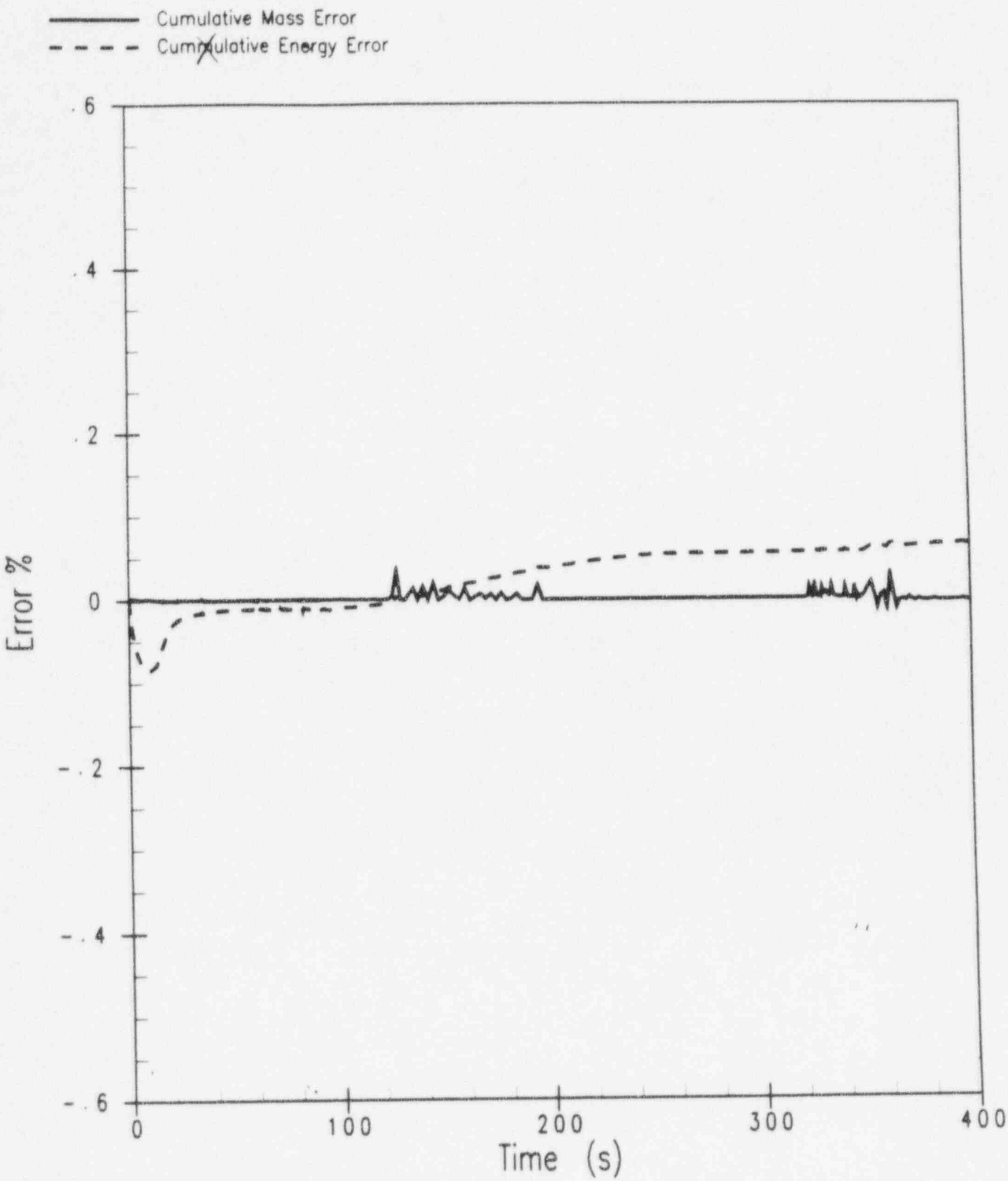


Figure 1 - Steam Line Break Transient, Mass and Energy Balance

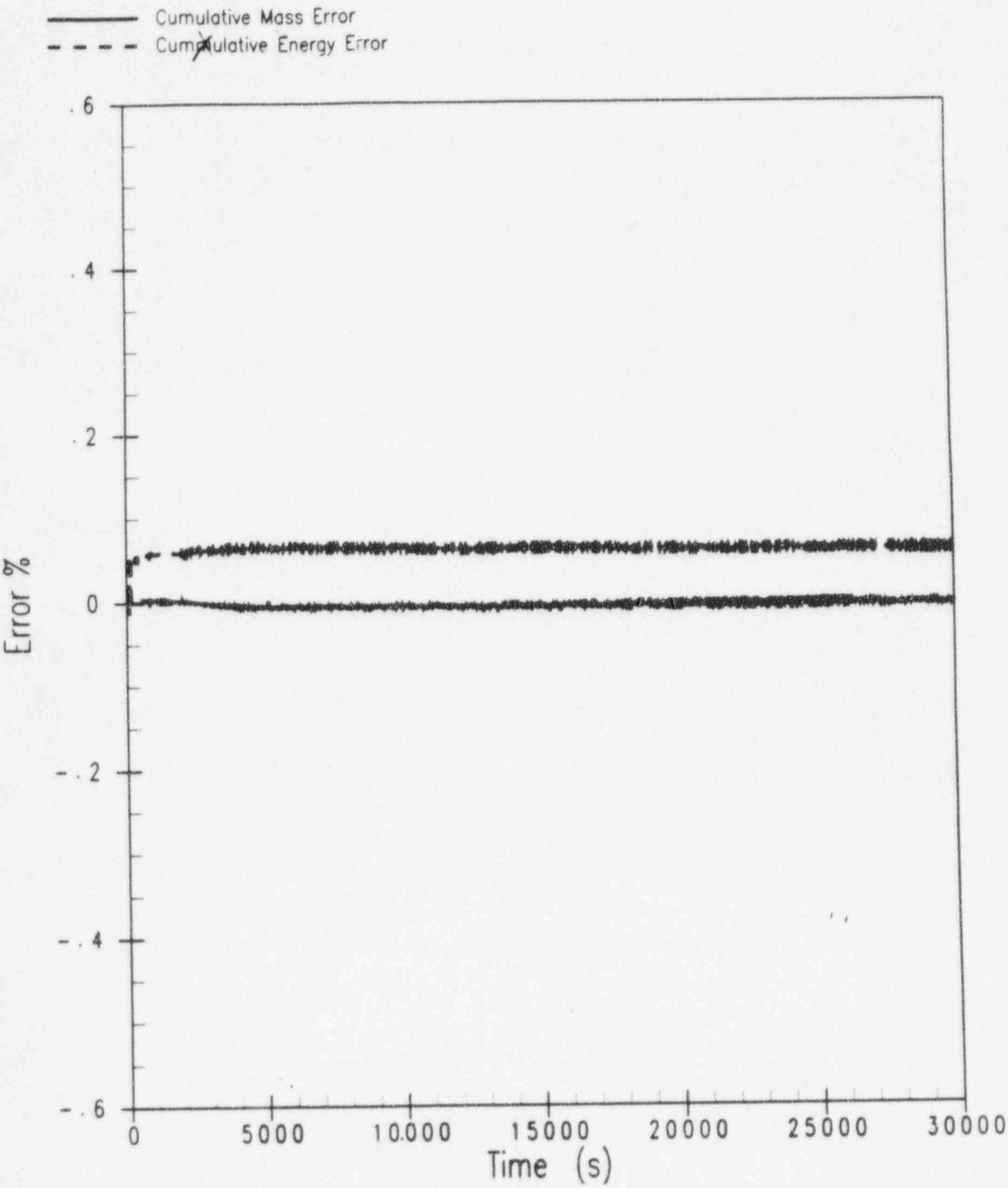


Figure 2 - Loss of Normal Feedwater Transient, Mass and Energy Balance

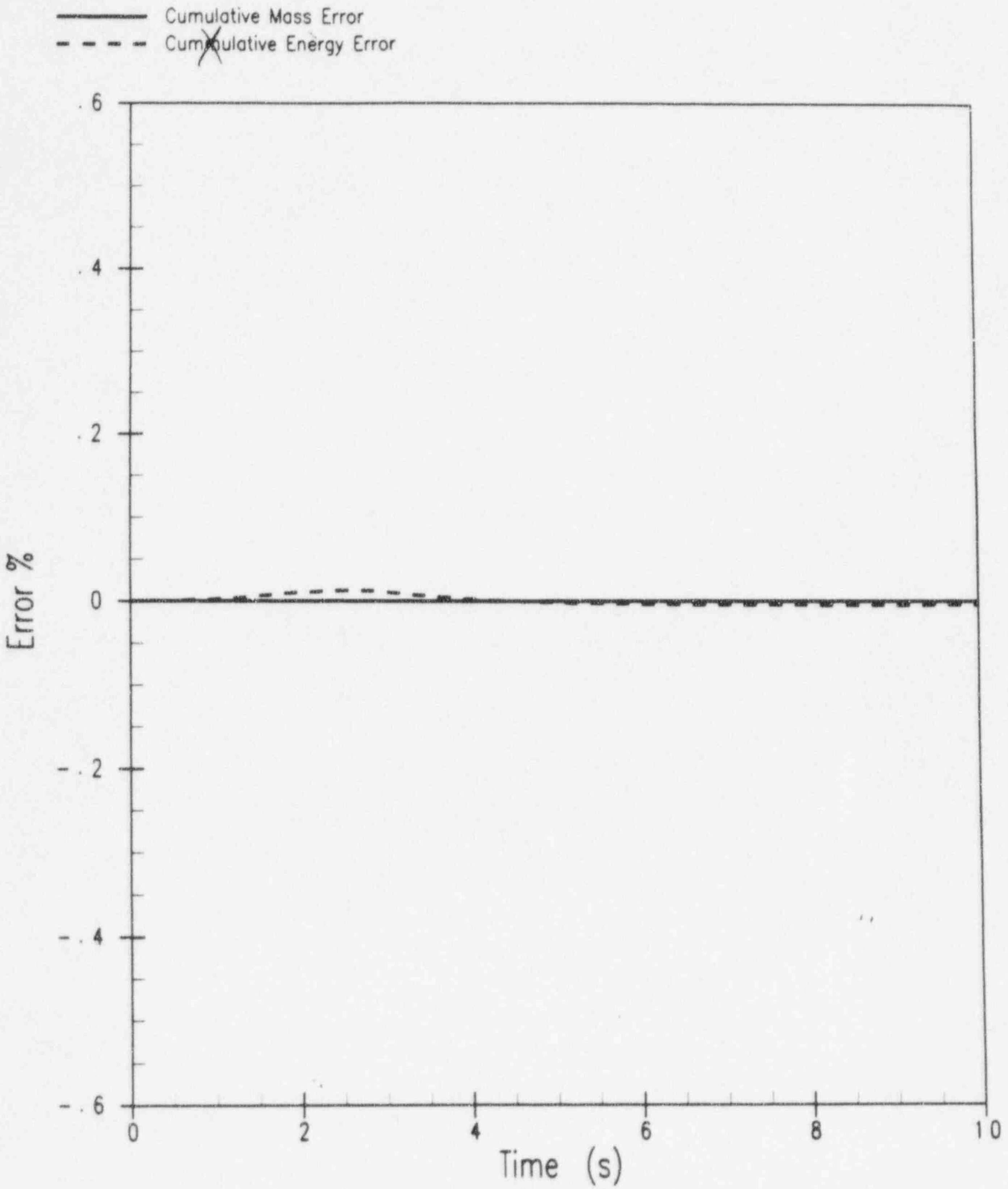


Figure 3 - Complete Loss of Flow Transient, Mass and Energy Balance

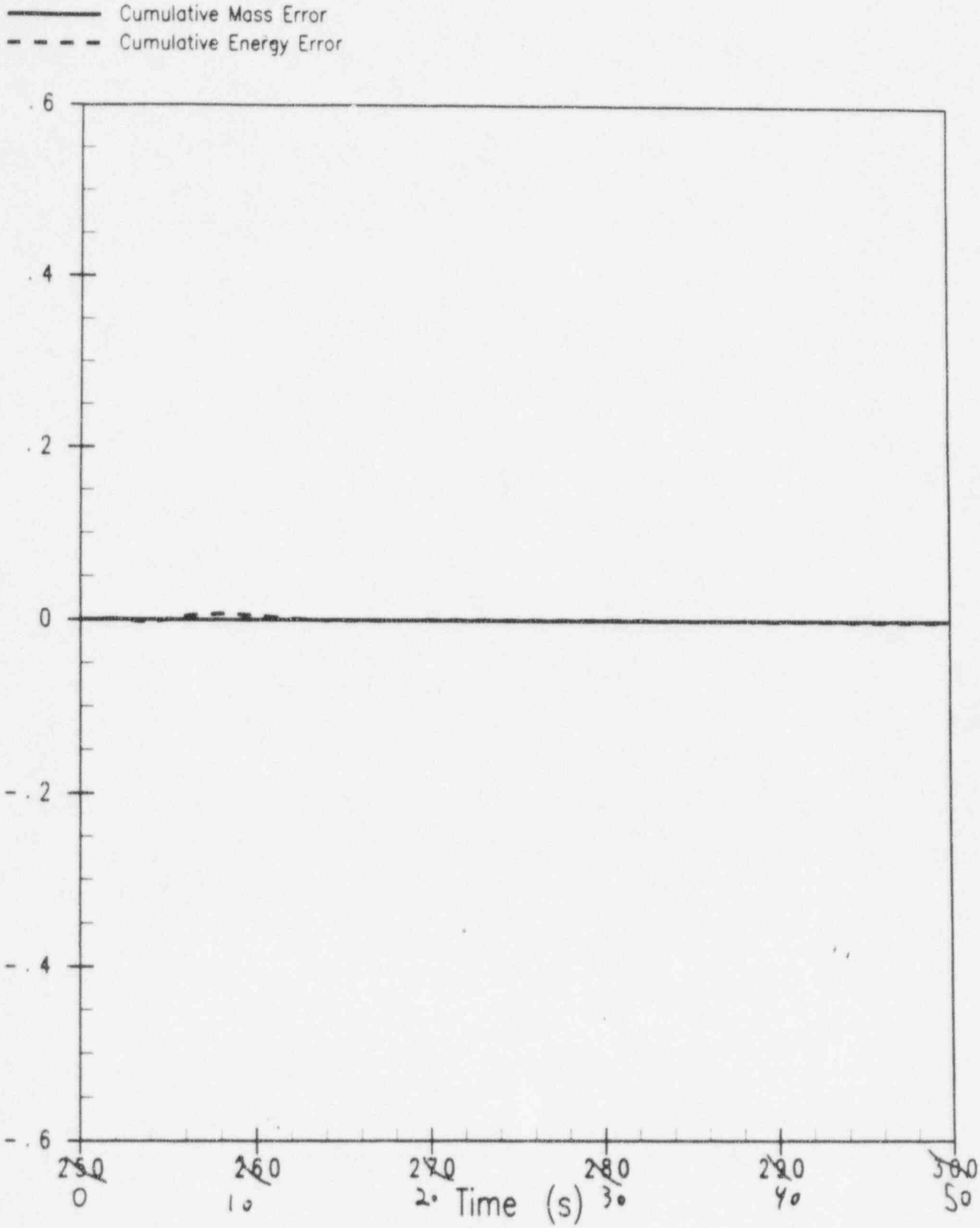


Figure 4 - Startup of an Inactive Loop Transient, Mass and Energy Balance

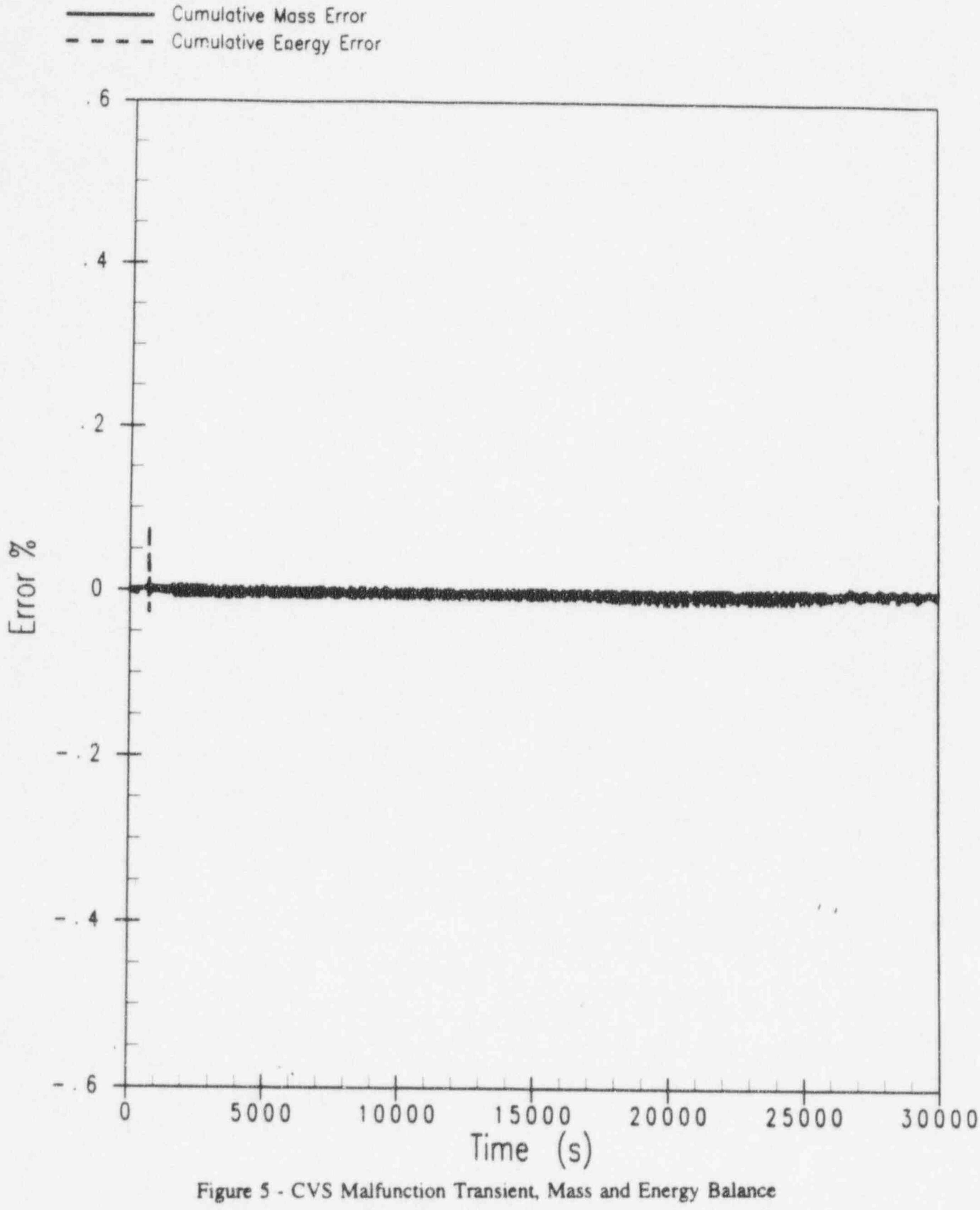


Figure 5 - CVS Malfunction Transient, Mass and Energy Balance

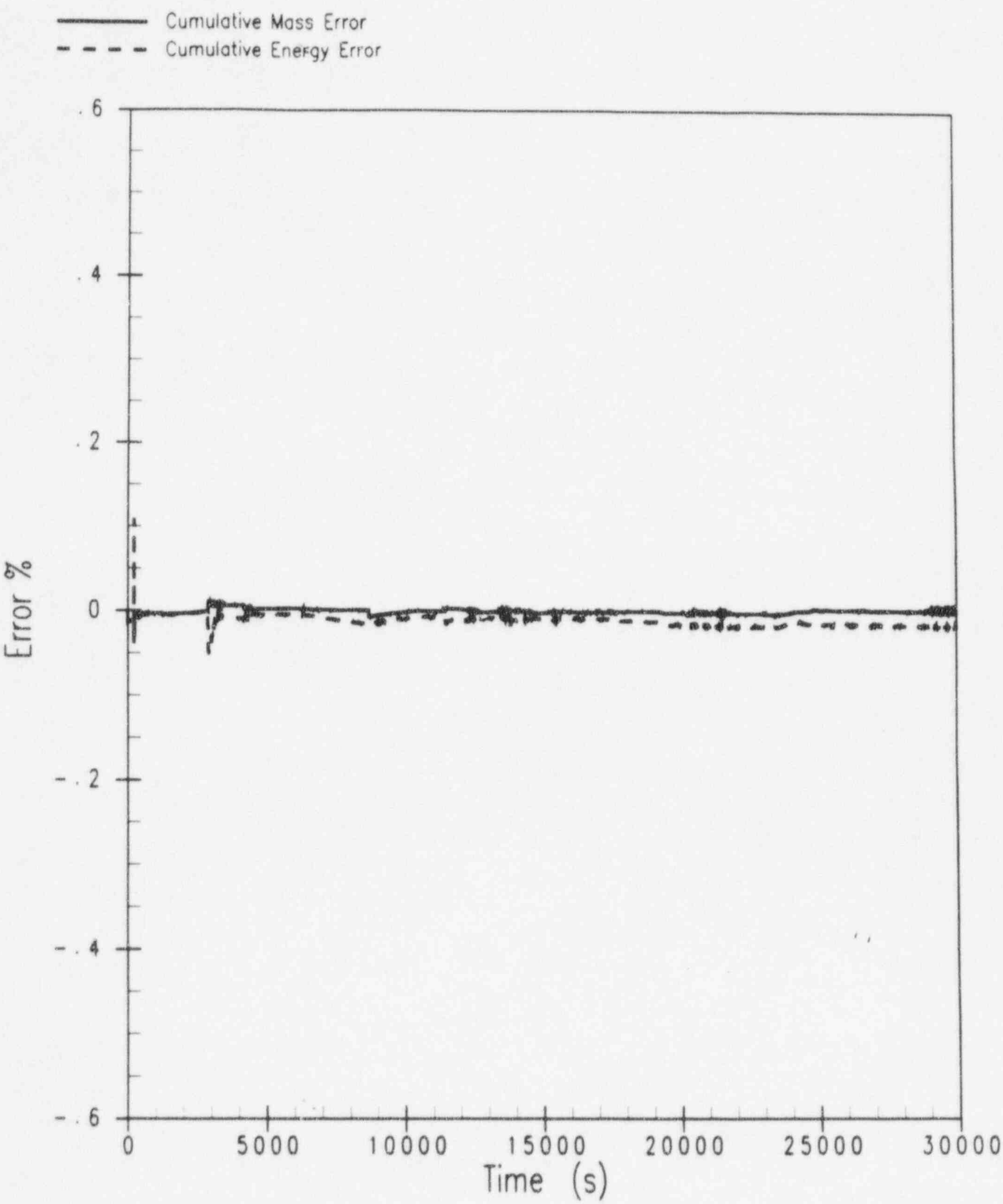


Figure 6 - Steam Generator Tube Rupture Transient, Mass and Energy Balance

SDSER Open Item 21.6.1.7-7

If choked flow is applied throughout the transients, Westinghouse needs to demonstrate that this approach is conservative in all cases using LOFTRAN for the AP600.

Response:

A description of the application of choked flow is provided below for the applicable transients.

Steam Generator Tube Rupture
The flow out of the break in a steam generator tube rupture may be choked or unchoked. The break flow model includes the geometry of the tube and simulates form and friction pressure losses. A summary of the tube rupture break flow model and relevant equations used, is shown on pages 3-2 through 3-6 of WCAP-10698-P-A, which is approved for use with operating PWRs by the NRC.

Steam Line Break
The LOFTRAN steam line break flow model assumes choked flow continuously throughout the duration of the event. The model remains unchanged from that used on previously licensed operating plants. This is a conservative assumption for steam line break. Using the maximum choked flow from the break, results in a bounding cool down of the RCS. For evaluation of the core thermal hydraulic response, maximizing the cool down results in a larger core return to power.

With respect to evaluating the impact of steam line break releases to the containment, the most limiting cases are large double ended ruptures. Peak containment pressure occurs when the faulted steam generator drys out. Use of choked flow throughout the steam line break analysis in this case maximizes the rate of mass and energy release to the containment which is conservative for containment performance evaluation.

Feed Line Break
The feed line break is a loss of secondary side heat sink transient. Following reactor trip on low steam generator level, the event is mitigated by the heat removal capability of the PRHR in conjunction with fluid remaining in the steam generators. The severity of the event is increased if the post reactor trip steam generator inventory is reduced. In the AP600 feed line break analysis prior to reactor trip, the break area is assumed to be just large enough that a complete loss of normal feedwater to both steam generators occurs. In other words, the feedwater flow into or out of both steam generators is zero. This minimizes the inventory in both steam generators at the time of reactor trip because the level in both steam generators is at the low level reactor trip setpoint. At reactor trip a full double ended rupture is initiated and the maximum choked flow from the break is assumed. This conservatively depletes inventory from the faulted steam generator rapidly such that the heat removal rate from the faulted steam generator is negligible. Formulating the event in this manor conservatively bounds break size, effects of the main feedwater piping resistance and any interactions with the main feedwater system.

Westinghouse Status: Closed

SDSER Confirmatory Item 21.5.4-1

Westinghouse must use the Adjusted WRB-2 correlation for the departure from nucleate boiling Ratio (DNBR) calculation if the local area mass flux in the hot channel is between 2.34×10^6 and 5.08×10^6 kg/hr-m^2 (0.48×10^6 and 1.04×10^6 lb$_m$/hr-ft^2).

Response:

No Westinghouse action or response required.

Westinghouse Status: Closed

SDSER Confirmatory Item 21.5.4-2

Westinghouse must use the WRB-2 correlation for the DNBR calculation if the local area mass flux in the hot channel is between 4.9×10^6 and 1.8×10^7 kg/hr-m^2 (1.0×10^6 and 3.7×10^6 lb$_m$/hr-ft^2).

Response:

The lower range of WRB-2 correlation (Per WCAP 10444-P-A, and the subsequent NRC Safety Evaluation Report) is 0.9E6 lbm/hr-ft2 instead of 1.0E6 lbm/hr-ft2. This clarification was confirmed in a 6/19/96 teleconference between Westinghouse (John Butler) and NRC (Tony Attard). No further Westinghouse action required.

Westinghouse Status: Closed

SDSER Confirmatory Item 21.5.4-3

The staff's DNBR acceptance applies only to VANTAGE 5-H fuel assemblies.

Response:

No Westinghouse action or response required.

Westinghouse Status: Closed

AP600

Methodology and Sample Verification Calculations for AP600 Partial Loss of Flow Transients and Locked Rotor/Broken Shaft Transients

September 1996

E. C. Carlin
Westinghouse Electric Corporation

Table of Contents

1. Introduction

2. Definitions & Terminology

3. 2 of 4 Partial Loss of Flow Coast Down Methodology

3.1 Methods Used for Partial Loss of Forced RCS Flow
3.2 Calculational Procedure
3.3 Results and Verification of the Partial Loss of Flow Auxiliary Code

4. Locked Rotor or Broken Shaft Followed by Loss of AC Power Methodology

4.1 Methods Used for Locked Rotor or Broken Shaft
4.2 Calculational Procedure
4.3 Results and Verification of the Locked Rotor/Broken shaft Auxiliary Code

Appendices

A Plant Design Data Used in Calculations

B RCP Head, Torque, Speed & Flow Characteristics

1. Introduction

In the Supplement to the Draft Safety Evaluation Report Related to the Certification of the AP600 Design dated April 1996, the NRC has identified open item 21.6.1.7-3 related to the LOFTRAN code and methods used for non-LOCA design basis analyses. This report provides a response to Open Item 21.6.1.7-3. This open item states:

> Westinghouse needs to submit a detailed example of how it used auxiliary programs, hand calculations, and conservative assumptions to model pump trips and startups in LOFTRAN.

In the following sections is a response to the open item that supplies detailed explanation of the auxiliary codes used to calculate the RCS flow transients following a partial loss of flow event and a locked rotor or broken RCP shaft event. Also included are hand calculations which further illustrate the operation of the auxiliary codes and verify those codes.

2. Definitions and Terminology

Sections 3 and 4 summarize the methodology used for calculating the RCS flow rates during a partial loss of flow and a locked rotor or broken shaft transients. Also included are the equations and sample hand calculations which implement the equations used by the methodology. A schematic of the RCS loop as used in the calculations is shown in Figure 2-1. Listed below are definitions of the variables used in the equations.

n	-	Reactor coolant pump or cold leg identifier. n = 1A, 1B, 2A or 2B (see Figure 2-1)
j	-	Reactor coolant loop identifier. j = 1 or 2 (see Figure 2-1)
QCL_n	-	cold leg volumetric flow [gpm]
WCL_n	-	cold leg mass flow [lbm/sec]
S_n	-	RCP speed [rpm or radians/sec]
dS_n/dt	-	change in reactor coolant pump speed [radians/sec^2]
$DP_{RCP\ n}$	-	pump head for RCP n [psi]
WC	-	Core, vessel mass flow rate [lbm/sec]
QCIN	-	Vessel inlet volumetric flow rate [gpm]
QC	-	Core volumetric flow rate [gpm]
QCOUT	-	Vessel outlet region volumetric flow rate [gpm]
WHL_j	-	Loop j hot leg mass flow rate [lbm/sec]
QHL_j	-	Loop j hot leg volumetric flow rate [gpm]
$QSGT_j$	-	Loop j steam generator tube volumetric flow rate [gpm]
$QSGO_j$	-	Loop j steam generator outlet plenum volumetric flow rate [gpm]

K_i	-	lumped pressure loss coefficient for region i [psi/gpm^2]		
	where i =	CL	-	cold leg
		RVI	-	reactor vessel inlet region
		C	-	core active fuel region
		CO	-	core outlet region
		RVO	-	reactor vessel outlet region
		HL	-	hot leg
		SGI	-	steam generator inlet nozzle and plenum
		SGT	-	steam generator tubes
		SGO	-	steam generator outlet nozzle and plenum
		PUMP	-	non-operating reactor coolant pump

t	-	time [seconds]
Δt	-	time step size [seconds]
$DP_{RCP\ n}$	-	pump head for RCP n [psi]
$T_{h\ RCP\ n}$	-	hydraulic torque for RCP n [ft lb]
T_m	-	motor torque [ft lb]
WIND	-	RCP motor windage loss, ft-lb-sec^2
FRICT	-	RCP frictional loss term, ft-lb-sec$^{1/2}$
PUMPI	-	RCP rotating inertia, lbm-ft^2
ρ_{HL}	-	fluid density in the hot leg [lbm/ft^3]
ρ_{CL}	-	fluid density in the cold leg [lbm/ft^3]
ρ_{AVG}	-	Average of ρ_{HL} and ρ_{HL}. Used as the fluid density in the core and the steam generator tubes. [lbm/ft^3]

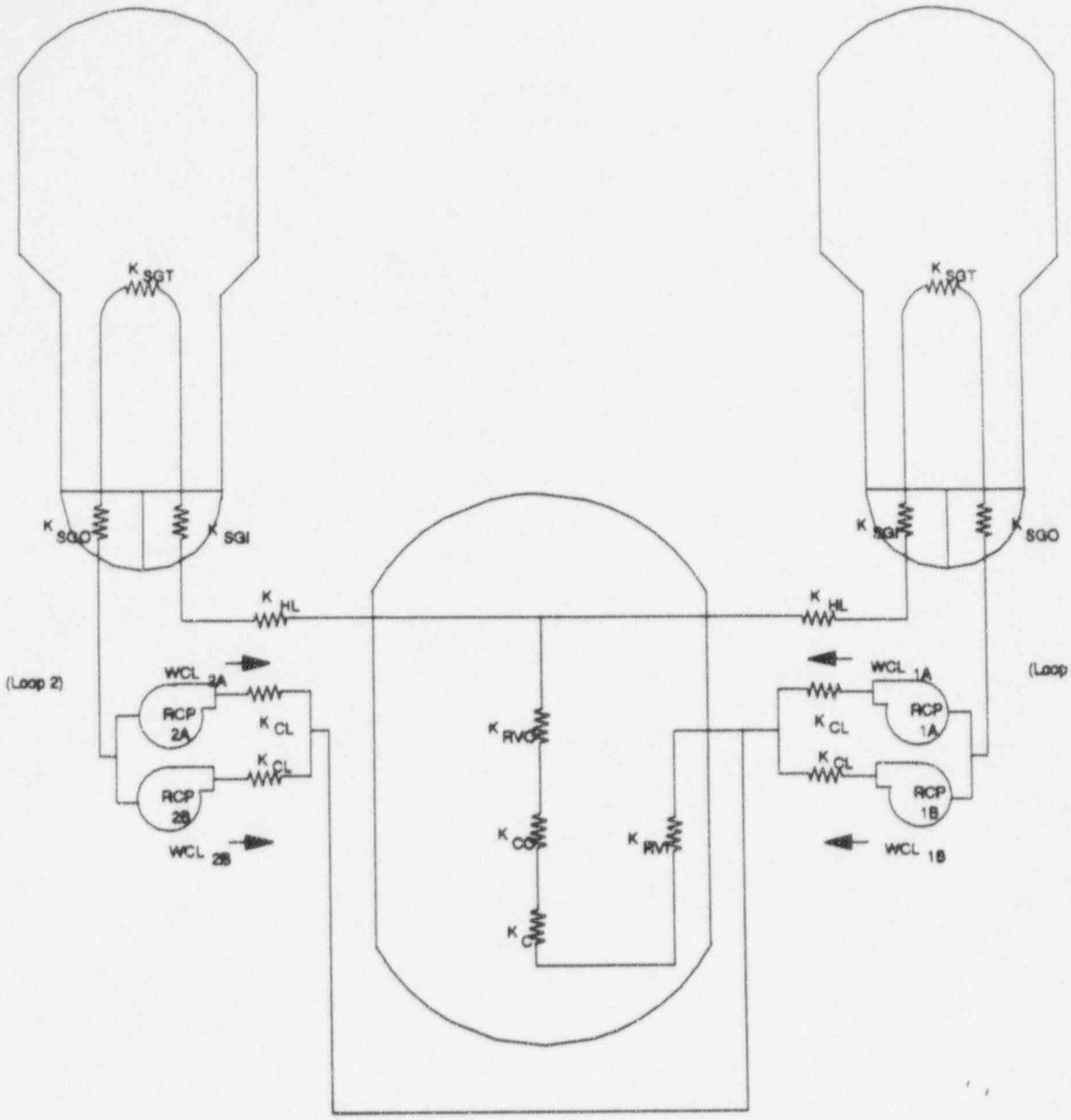

K SGT
K SGT
K SGO
K SGI
K SGI
K SGO
K HL
K HL
(Loop 2)
(Loop 1
WCL 2A
WCL 1A
RCP 2A
RCP 1A
K CL
K CL
K CL
K CL
RCP 2B
RCP 1B
K RVO
K CO
K RVT
K C
WCL 2B
WCL 1B

Figure 2-1

3. 2 of 4 Partial Loss of Flow Coast Down Methodology

3.1 Methods Used for Partial Loss of Forced RCS Flow

In the partial loss of flow analysis presented in the SSAR, two of the four RCPs are assumed to coast down. With the AP600 power supply arrangement, the two RCPs coasting down will be on opposing RCS loops. The major phenomenon associated with this event is the net flow delivered to the reactor core. The actual flow in the cold legs is important only for predicting when a low flow reactor trip will occur. The duration of the event is very short (less than 10 seconds).

The net flow loop flows for this event are calculated using a small auxiliary code (~350 line) and hand calculations. The loop flows are then input to LOFTRAN as the transient forcing functions. Section 3.2 summarizes the calculational procedure used in this code. Section 3.3 summarizes results from the code and also performs hand calculations. The hand calculations illustrate how the code works and also verify the code.

3.2 Calculational Procedure

The following procedure summarizes the calculational steps performed by the auxiliary code for calculating the transient loop flow rates during a partial loss of flow with 1 reactor coolant pump in each loop coasting down.

Referring to the schematic in Figure 2-1, RCP 1B and 2B are assumed to coast down in the following calculational procedure.

<u>Procedure for calculating partial loss of forced RCS flow with two RCPs coasting down</u>

<u>Assumptions</u>

- The inertia of the RCS fluid is conservatively ignored.
- Referring to Figure 2-1, RCPs 1B and 2B are faulted and assumed to be coasting down.
- Referring to Figure 2-1, RCPs 1A and 2A are unfaulted and assumed to remain at nominal reactor coolant pump speed.
- Fluid density in each region remains constant over the transient period.
- Mass flow rate is uniform through the RCS loop.
- The flows in loops 1 and 2 are symmetric and equal.

Step 0) Set initial conditions

- Initialize time (t = 0.0 seconds)
- Reactor coolant pumps are assumed to be operating at nominal speeds.

  $S_{1A} = S_{1B} = S_{2A} = S_{2B}$ = nominal operating speed

- Cold leg flow rates are assumed to be at nominal full flow values

$QCL_{1A} = QCL_{1B} = QCL_{2A} = QCL_{2B}$ = nominal full flow value

- Set RCS fluid densities (ρ_{CL}, ρ_{HL} & ρ_{AVG})

Step 1) Increment time

$t = t + \Delta t$

Step 2) Calculate RCP speed of pumps coasting down

The change in RCP speed is calculated based on the following

$$\frac{dS_{1B}}{dt} = \frac{(T_m - T_h - WIND \times S^2 - FRICT \times S^{1/2})}{PUMPI \,/\, g_c}$$

where S_{1B} = RCP speed, radians/sec
dS_{1B}/dt = transient change in RCP speed with respect to time
T_m = torque supplied by the motor = 0.0 ft-lb for pumps coasting down
T_h = hydraulic torque on RCP impeller, ft-lb
WIND = RCP windage loss term, ft-lb-sec^2
FRICT = RCP friction loss term, ft-lb-sec$^{1/2}$
PUMPI = RCP rotating inertia, lbm-ft^2
g_c = 32.174 lbm-ft / lbf-sec^2

The speed of the faulted reactor coolant pumps at time equal to t+Δt is calculated using

$$S_{1B}^{t+\Delta t} = S_{1B}^{t} + \frac{dS_{1B}}{dt}\,\Delta t$$

Start of Outer Iteration Loop

Step 3)

- Estimate flow through RCP 1A (QCL_{1A})
- $WCL_{1A} = QCL_{1A} \times \rho_{CL}$ (0.002228 ft^3/sec/gpm)
- Calculate the pump head for RCP 1A ($DP_{RCP\,1A}$) from homologous curves

Start of Inner Iteration Loop

Step 4)

- If the speed of RCP 1B is less than 5% of nominal speed go to step 4A
  If the speed of RCP 1B is greater than 5% of nominal speed go to step 4B

Step 4A)

At low reactor coolant speeds, the bearing friction is the dominant force slowing the pump. Bearing frictional torque drops with the square root of pump speed. At low a speed of ~5% it is assumed that the bearings approach contact and rubbing resistance is increased to the point at which the pump is stopped. When this occurs the back flow through RCP 1B is calculated based pressure drop through cold leg 1A and the inner iteration loop calculations can be skipped.

$$DP_{1A} = DP_{RCP\ 1A} - (K_{CL} \times QCL_{1A}^{2})$$

$$DP_{1B} = DP_{1A}$$

$$QCL_{1B} = -\sqrt{\frac{DP_{1B}}{K_{CL} + K_{PUMP}}}$$

and

$$WCL_{1B} = QCL_{1B} \times \rho_{CL}\ (0.002228\ ft^3/sec/gpm)$$

Skip inner iteration loop and jump to Step 7

Step 4B)

- Estimate flow through RCP 1B (QCL_{1B})
- $WCL_{1B} = QCL_{1B} \times \rho_{CL}$ (0.002228 ft^3/sec/gpm)
- Calculate the pump head for RCP 1B ($DP_{RCP\ 1B}$) from homologous curves

Step 5)

- Calculate the change in pressure from the inlet of RCP 1A through cold leg 1A to the reactor vessel inlet .

$$DP_{1A} = DP_{RCP\ 1A} - (K_{CL} \times QCL_{1A}^2)$$

- Calculate the change in pressure from the inlet of RCP 1B through cold leg 1B to the reactor vessel inlet .

$$DP_{1B} = DP_{RCP\ 1B} - (K_{CL} \times QCL_{1B} \times |QCL_{1B}|)$$

Step 6) Check for convergence in the inner iteration loop

$E_1 = DP_{1A} - DP_{1B}$

- Convergence if the absolute value of $E_1 \leq$ convergence criteria (0.1 psi). Go to Step 7.

- If E_1 is negative and the magnitude of E_1 is greater than the convergence criteria then;

  DP_{1B} is larger than DP_{1A}. Increase the estimated flow in RCP 1B to increase the pressure drop and decrease the pump head. Go back to Step 4.

- If E_1 is positive and the magnitude of E_1 is greater than the convergence criteria then;

  DP_{1B} is smaller than DP_{1A}. Decrease the estimated flow in RCP 1B to decrease the pressure drop and increase the pump head. Go back to Step 4.

<u>End of Inner Iteration Loop</u>

Step 7) Update the vessel, hot leg and steam generator flow rates based on the estimates for cold leg flow rates

$WC = 2\ (WCL_{1A} + WCL_{1B})$

$QCIN = WC\ /\ (\ (\rho_{CL})\ (0.002228\ ft^3/sec/gpm)\ )$

$QC = WC\ /\ (\ (\rho_{AVG})\ (0.002228\ ft^3/sec/gpm)\ )$

$QCOUT = WC\ /\ (\ (\rho_{HL})\ (0.002228\ ft^3/sec/gpm)\ )$

$WHL_1 = WCL_{1A} + WCL_{1B}$

QHL_i = WHL_i / ((ρ_{HL}) (0.002228 ft^3/sec/gpm))

$QSGT_i$ = WHL_i / ((ρ_{AVG}) (0.002228 ft^3/sec/gpm))

Step 8) Calculate the pressure loss from the outlet of RCP 1A through the cold leg, vessel, hot leg and steam generator to the inlet of RCP 1A.

$$DP_{RCS\,1} = (K_{CL}\,QCL_{1A}^2) + (K_{RVI}\,QCIN^2) + (K_C\,QC^2) + ([K_{CO} + K_{RVO}]\,QCOUT^2) + ([K_{HL} + K_{SGI}]\,QHL_1^2) + (K_{SGT}\,QSGT_1^2) + (K_{SGO}\,[QCL_{1A} + QCL_{1B}]^2)$$

Step 9) Check for convergence in outer iteration loop

$E2 = DP_{RCP\,1A} - DP_{RCS\,1}$

- Convergence if the absolute value of $E_2 \leq$ convergence criteria (1.0 psi). Go to Step 1.

- If the E_2 is negative and the magnitude of E_2 is greater than the convergence criteria then;

  Pressure drop is higher than pump head. Reduce the estimate for WCL_{1A} to decrease the pressure drop and increase the pump head. Go to Step 3.

- If the E_2 is positive and the magnitude of E_2 is greater than the convergence criteria then;

  Pressure drop is lower than pump head. Increase the estimate for WCL_{1A} to increase the pressure drop and decrease the pump head. Go to Step 3.

3.3 Transient Flow Coast Down Results

A small auxiliary code was used to perform the calculations outlined in Section 3.2 for a partial loss of RCS flow transient.

In the transient analyzed, reactor coolant pumps 1B and 2B (see Figure 2-1) are assumed to start coasting down at time equal 0.0 seconds. Reactors coolant pumps 1A and 2A are assumed to remain running at nominal operating speed. The results from the calculations are shown in Figure 3-1. As shown in Figure 3-1 the reactor coolant pump coasts down in ~ 9 seconds.

At low reactor coolant speeds, the bearing friction is the dominant force slowing the pump. Bearing frictional torque drops with the square root of pump speed. At low a speed of 5% it is assumed that the bearings approach contact and rubbing resistance is increased to the point at which the pump is stopped. In the case analyzed this occurs at 9.1 seconds and is illustrated in Figure 3-1.

The results from the auxiliary code calculations are used to develop a conservative time dependent RCS flow forcing function for use in the LOFTRAN SSAR analyses. Table 3-1 illustrates the development of the RCS flow which is used as input to LOFTRAN. Table 3-1 summarized selected time step results for Loop 1 as calculated by the auxiliary code. The flow rates for the faulted and unfaulted cold legs are summed to obtain the net cold leg flow rate. For input to LOFTRAN, values which bound the auxiliary code predicted net loop flow rates are used. An additional conservatism, the values used in LOFTRAN SSAR analysis have been reduced by approximately 5%.

Hand calculations that illustrate the partial loss of flow calculation procedure outlined in Section 3.2 are shown in Table 3-2 through 3-5. Hand calculations are shown for the following time periods:

Table 3-2	-	Time = 0.0 to 0.1 seconds
Table 3-3	-	Time = 0.1 to 0.2 seconds
Table 3-4	-	Time = 3.5 to 3.6 seconds

Tables 3-2 through 3-3 illustrate the initial change in flow from normal steady state flows through the next two time steps of the transient calculation. Table 3-4 shows a time step from the middle of the transient. The procedure outlined in Section 3.2 is uses an iterative approach to calculate the system flow rates. The procedure iterates on the flow rates in cold leg 1A and cold leg 1B until a pressure balance around the RCS loop is obtained.

In the hand calculations shown in Table 3-2 through 3-4, the final flow rates from the auxiliary code are used as the estimates for cold leg 1A & 1B flow rates. Tables 3-2 through 3-4 perform one iteration and demonstrate that a pressure balance around to RCS loop is obtained from the auxiliary code. The auxiliary code calculated values presented in Table 3-1 compare within the round off accuracy expected to the hand calculations of Table 3-2 through 3-4. Tables 3-2 through 3-4 verify that the auxiliary code is performing correctly.

Table 3-1 Comparison of Auxiliary Code Calculated Flows to LOFTRAN SSAR Analysis Flows

Time (seconds)	Auxiliary Code Calculated Flow Rates (See Procedure in Section 3.2)						Net Loop Flow Used in LOFTRAN SSAR Transient Analyses (fraction of initial)
	Unfaulted Cold Leg (RCP 1A)		Faulted Cold Leg (RCP 1B)		Net Loop Flow		
	Speed (radians/sec)	Flow (gpm)	Speed (radians/sec)	Flow (gpm)	(gpm)	(fraction of initial)	
0.0	183.57	48300.0	183.57	48300.0	96600.0	1.0	1.0
0.1	183.57	49432.0	177.20	45507.7	94939.7	0.9828	---
0.2	183.57	50511.0	171.22	42961.7	93472.7	0.9676	---
0.3	183.57	51539.4	165.62	40502.8	92042.2	0.9528	---
0.5	183.57	53453.8	155.37	35768.6	89222.4	0.9236	0.8774
1.0	183.57	57387.3	134.34	25049.6	82436.9	0.8534	0.8129
1.5	183.57	60308.9	118.80	16744.8	77053.7	0.7977	0.7568
2.0	183.57	62862.2	106.99	6672.8	69535.0	0.7198	0.6817
2.5	183.57	64137.6	97.61	1433.5	65571.1	0.6788	0.6479
3.0	183.57	65010.9	89.85	-2195.5	62815.4	0.6503	0.6259
3.5	183.57	65792.4	82.99	-4824.0	60968.4	0.6311	0.6020
4.0	183.57	66202.0	76.61	-6931.2	59270.8	0.6136	0.5833
6.0	183.57	67285.7	50.18	-13207.4	54078.3	0.5598	0.5308
8.0	183.57	68185.9	23.30	-16323.4	51862.5	0.5369	0.5050
10.0	183.57	70051.4	0.0	-26958.6	43092.8	0.4461	0.4076

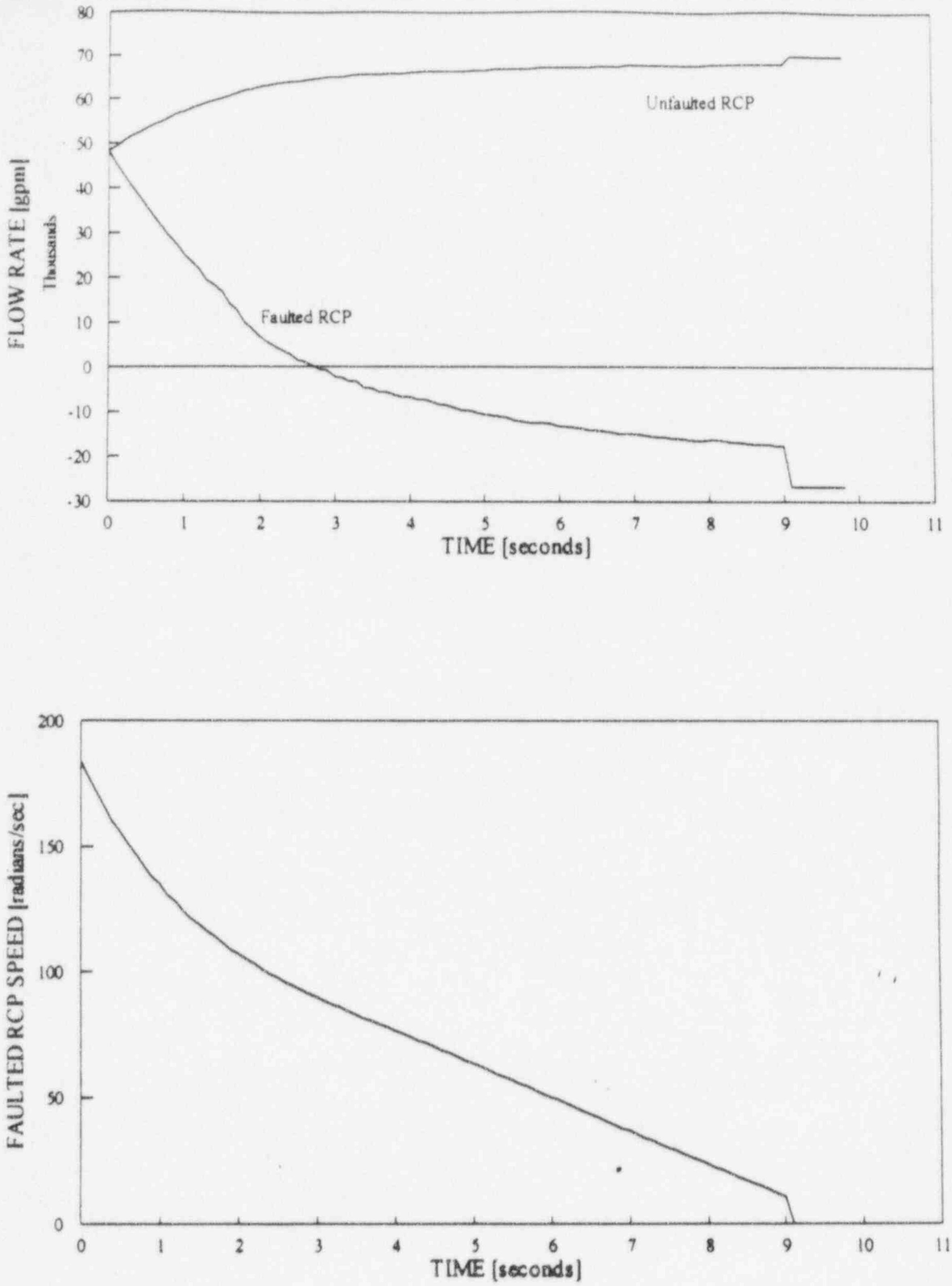

FLOW RATE [gpm]
Thousands
Unfaulted RCP
Faulted RCP
TIME [seconds]
FAULTED RCP SPEED [radians/sec]
TIME [seconds]

Figure 3-1

TABLE 3-2 (page 1 of 4) Verification Calculations for 2 out 4 Partial Loss of Flow Transient
Time 0.0 to 0.1 Seconds

Step 0) Set initial conditions

- Initialize time (t = 0.0 seconds)
- Reactor coolant pumps are assumed to be operating at nominal speeds.
  $S_{1A} = S_{1B} = S_{2A} = S_{2B}$ = nominal operating speed = 1753. rpm (183.57 radians/sec)
- Cold leg flow rates are assumed to be at nominal full flow values
  $QCL_{1A} = QCL_{1B} = QCL_{2A} = QCL_{2B}$ = Minimum Measured Flow = 48300. gpm
- Set RCS Fluid Densities
  ρ_{CL} = 47.892 lbm/ft^3 ρ_{HL} = 43.014 lbm/ft^3 $\rho_{AVG} = (\rho_{CL} + \rho_{HL}) / 2$ = 45.453 lbm/ft^3

Step 1) Increment time
$t = t + \Delta t = 0.0 + 0.1 = 0.1$ seconds

Step 2) Calculate the speed of the pump coasting down (RCP 1B)

$$\frac{dS_{1B}}{dt} = \frac{(T_m - T_{h\ RCP\ 1B} - \text{WIND} \times (S_{1B}^{t=0.0})^2 - \text{FRICT} \times (S_{1B}^{t=0.0})^{1/2})}{\text{PUMPI} / g_c}$$

$T_{h\ RCP\ 1B}$ = 8970.89 ft-lb, hydraulic torque at 1753. rpm, 48300 gpm & 47.892 lbm/ft^3 (see Table B-2)

$$\frac{dS_{1B}}{dt} = \frac{(0.0) - 8970.89\ \text{ft-lb} - (0.0254\ \text{ft-lb-sec}^2) \times (183.57\ \text{radians/sec})^2 - (6.3\ \text{ft-lb-sec}^{1/2} \times (183.57\ \text{radians/sec})^{1/2}}{(5000.\ \text{lbm-ft}^2) / (32.174\ \text{lbm-ft/lbf-sec}^2)}$$
$$= -63.78 \text{radians/sec}$$

$$S_{1B}^{t=0.1} = S_{1B}^{t=0.0} + \frac{dS_{1B}}{dt} \Delta t$$
$$= (183.57\ \text{radians/sec}) + (-63.78\ \text{radians/sec}^2)\ (0.1\ \text{sec})$$
$$= 177.19\ \text{radians/sec}$$
or
$$= 1692.0\ \text{rpm}$$

TABLE 3-2 (page 2 of 4)
Verification Calculations for 2 out 4 Partial Loss of Flow Transient
Time 0.0 to 0.1 Seconds

Step 3)

- Estimate flow through RCP 1A (unfaulted RCP)

QCL_{1A} = 49432.0 gpm

$WCL_{1A} = QCL_{1A} \times (\rho_{CL})$ (0.002228 ft^3/sec/gpm)
= (49432.0 gpm) (47.892 lbm.ft^3) (0.002228 ft^3/sec/gpm)
= 5274.56 lbm/sec

- Calculate the pump head for RCP 1A from homologous curves

$DP_{RCP\ 1A}$ = 87.056 psi — Pump head at 49432.0 gpm, 1753. rpm and 47.892 lbm/ft^3 (see Table B-2)

Step 4)

- Estimate flow through RCP 1B (faulted RCP)

QCL_{1B} = 45507.7 gpm

$WCL_{1B} = QCL_{1B} \times (\rho_{CL})$ (0.002228 ft^3/sec/gpm)
= (45507.7 gpm) (47.892 lbm/ft^3) (0.002228 ft^3/sec/gpm)

= 4855.83 lbm/sec

- Calculate the pump head for RCP 1B from homologous curves

$DP_{RCP\ 1B}$ = 86.755 psi — Pump head at 45507.7 gpm, 1692.0 rpm and 47.892 lbm/ft^3 (see Table B-2)

Step 5)

- Calculate the change in pressure from the inlet of RCP 1A through the cold leg to the reactor vessel inlet.

$DP_{1A} = DP_{RCP\ 1A} - (K_{CL}) (QCL_{1A})^2$
= 87.056 psi - (8.284×10^{-10} psi/gpm^2) (49432.0 gpm)^2
= 85.032 psi

TABLE 3-2 (page 3 of 4)
Verification Calculations for 2 out 4 Partial Loss of Flow Transient
Time 0.0 to 0.1 Seconds

- Calculate the change in pressure from the inlet of RCP 1B through the cold leg to the reactor vessel inlet.

$DP_{1B} = DP_{RCP\ 1B} - (K_{CL})\ (QCL_{1B})^2$
$= 86.755\ psi - (8.284x10^{-10}\ psi/gpm^2)\ (45507.7\ gpm)^2$
$= 85.039\ psi$

Step 6)

- Check for convergence in the inner iteration loop

$E_1 = DP_{1A} - DP_{1B}$
$= 85.032\ psi - 85.039\ psi$
$= -0.007\ psi$

The magnitude of $E_1 \leq 0.1$ psi, therefore the convergence criteria is met. Go to Step 7

Step 7) Update the vessel, hot leg, and steam generator flow rates based on the estimates for cold leg flow rates.

$WC = 2\ (WCL_{1A} + WCL_{1B})$
$= 2\ (\ 5274.56\ lbm/sec + 4855.83\ lbm/sec\ )$
$= 20260.78\ lbm/sec$

$QCIN = WC\ /\ (\ (\rho_{CL})\ (0.002228\ ft^3/sec/gpm)\ )$
$= (\ 20260.78\ lbm/sec\ )\ /\ (\ (47.892\ lbm/ft^3)\ (0.002228\ ft^3/sec/gpm)\ )$
$= 189879.47\ gpm$

$QC = WC\ /\ (\ (\rho_{AVG})\ (0.002228\ ft^3/sec/gpm)\ )$
$= (\ 20260.78\ lbm/sec\ )\ /\ (\ (45.453\ lbm/ft^3)\ (0.002228\ ft^3/sec/gpm)\ )$
$= 200068.36\ gpm$

$QCOUT = WC\ /\ (\ (\rho_{HL})\ (0.002228\ ft^3/sec/gpm)\ )$
$= (\ 20260.78\ lbm/sec\ )\ /\ (\ (43.014\ lbm/ft^3)\ (0.002228\ ft^3/sec/gpm)\ )$
$= 211412.73\ gpm$

$WHL_1 = WCL_{1A} + WCL_{1B}$
$= 5274.56\ lbm/sec + 4855.83\ lbm/sec$
$= 10130.39\ lbm/sec$

TABLE 3-2 (page 4 of 4)
Verification Calculations for 2 out 4 Partial Loss of Flow Transient
Time 0.0 to 0.1 Seconds

$QHL_1 = WHL_1 / ((\rho_{HL})(0.002228\ ft^3/sec/gpm))$
$= (10130.39\ lbm/sec) / ((43.014\ lbm/ft^3)(0.002228\ ft^3/sec/gpm))$
$= 105706.37$ gpm

$QSGT_1 = WHL_1 / ((\rho_{AVG})(0.002228\ ft^3/sec/gpm))$
$= (10130.39\ lbm/sec) / ((45.453\ lbm/ft^3)(0.002228\ ft^3/sec/gpm))$
$= 100034.18$ gpm

Step 8) Calculate the pressure loss from the outlet of RCP 1A through the cold leg, vessel, hot leg and steam generator to the inlet of RCP 1A.

$$DP_{RCS\,1} = (K_{CL}\ QCL_{1A}^2) + (K_{RVI}\ QCIN^2) + (K_C\ QC^2) + ([K_{CO} + K_{RVO}]\ QCOUT^2) + ([K_{HL} + K_{SGI}]\ QHL_1^2) + (K_{SGT}\ QSGT_1^2) + (K_{SGO}\ [QCL_{1A} + QCL_{1B}]^2)$$

$$\begin{aligned} DP_{RCS\,1} = & (8.284\times10^{-10}\ psi/gpm^2)\ (49432.0\ gpm)^2 \\ & +(3.979\times10^{-10}\ psi/gpm^2)\ (189879.47\ gpm)^2 \\ & +(3.017\times10^{-10}\ psi/gpm^2)\ (200068.36\ gpm)^2 \\ & +(0.449\times10^{-10}\ psi/gpm^2 + 0.5827\times10^{-10}\ psi/gpm^2)\ (211412.73\ gpm)^2 \\ & +(6.250\times10^{-10}\ psi/gpm^2 + 4.756\times10^{-10}\ psi/gpm^2)\ (105706.37\ gpm)^2 \\ & +(38.02\times10^{-10}\ psi/gpm^2)\ (100034.18\ gpm)^2 \\ & +(4.143\times10^{-10}\ psi/gpm^2)\ (49432.0\ gpm + 45507.7\ gpm)^2 \\ = & 87.136\ psi \end{aligned}$$

Step 9) Check for convergence in outer iteration loop

$E_2 = DP_{RCP\,1A} - DP_{RCS\,1}$
$= 87.056$ psi $- 87.136$ psi
$= -0.080$ psi

The magnitude of $E_2 \leq$ convergence criteria of 1.0 psi. Therefore the flow estimates of 49432.0 gpm for RCP 1A and 45507.7 gpm for RCP 1B are correct.

Go to the next time step.

TABLE 3-3 (page 1 of 4)
Verification Calculations for 2 out 4 Partial Loss of Flow Transient
Time = 0.1 to 0.2 Seconds

Step 1) Increment time

$t = t + \Delta t = 0.1 + 0.1 = 0.2$ seconds

Step 2) Calculate the speed of the pump coasting down (RCP 1B)

$$\frac{dS_{1B}}{dt} = \frac{(T_m - T_h - \text{WIND} \times (S_{1B}^{t=0.1})^2 - \text{FRICT} \times (S_{1B}^{t=0.1})^{1/2})}{\text{PUMPI} / g_c}$$

$T_{h\ RCP\ 1B}$ = 8401.66 ft-lb, hydraulic torque at 45507.7 gpm, 1692.0 rpm (177.19 radians/sec), & 47.892 lbm/ft^3 (see Table B-2).

$$\frac{dS_{1B}}{dt} = \frac{(0.0) - 8401.66 \text{ ft-lb} - (0.0254 \text{ ft-lb-sec}^2) \times (177.19 \text{ radians/sec})^2 - (6.3 \text{ ft-lb-sec}^{1/2} \times (177.19 \text{ radians/sec})^{1/2}}{(5000. \text{ lbm-ft}^2) / (32.174 \text{ lbm-ft/lbf-sec}^2)}$$

$$= -59.73 \text{radians/sec}$$

$$S_{1B}^{t=0.2} = S_{1B}^{t=0.1} + \frac{dS_{1B}}{dt} \Delta t$$

$$= (177.19 \text{ radians/sec}) + (-59.73 \text{ radians/sec}^2)(0.1 \text{ sec})$$

$$= 171.22 \text{ radians/sec}$$

or

$$= 1635.0 \text{ rpm}$$

Step 3)

- Estimate flow through RCP 1A (unfaulted RCP)

QCL_{1A} = 50511.0 gpm

$WCL_{1A} = QCL_{1A} \times (\rho_{CL})$ (0.002228 ft^3/sec/gpm)
= (50511.0 gpm) (47.892 lbm.ft^3) (0.002228 ft^3/sec/gpm)
= 5389.69 lbm/sec

- Calculate the pump head for RCP 1A from homologous curves

$DP_{RCP\ 1A}$ = 84.190 psi Pump head at 50511.0 gpm, 1753. rpm & 47.892 lbm/ft^3 (see Table B-2)

TABLE 3-3 (page 2 of 4)
Verification Calculations for 2 out 4 Partial Loss of Flow Transient
Time = 0.1 to 0.2 Seconds

Step 4)

- Estimate flow through RCP 1B (faulted RCP)

QCL_{1B} = 42961.7 gpm

$WCL_{1B} = QCL_{1B} \times (\rho_{CL})$ (0.002228 ft³/sec/gpm)
= (42961.7 gpm) (47.892 lbm/ft³) (0.002228 ft³/sec/gpm)
= 4584.16 lbm/sec

- Calculate the pump head for RCP 1B from homologous curves

$DP_{RCP\ 1B}$ = 83.518 psi — Pump head at 42961.7 gpm, 1635.0 rpm & 47.892 lbm/ft³ (see Table B-2)

Step 5)

- Calculate the change in pressure from the inlet of RCP 1A through the cold leg to the reactor vessel inlet.

$$DP_{1A} = DP_{RCP\ 1A} - (K_{CL})(QCL_{1A})^2$$
$$= 84.190 \text{ psi} - (8.284\times10^{-10} \text{ psi/gpm}^2)(50511.0 \text{ gpm})^2$$
$$= 82.076 \text{ psi}$$

- Calculate the change in pressure from the inlet of RCP 1B through the cold leg to the reactor vessel inlet.

$$DP_{1B} = DP_{RCP\ 1B} - (K_{CL})(QCL_{1B})^2$$
$$= 83.518 \text{ psi} - (8.284\times10^{-10} \text{ psi/gpm}^2)(42961.7 \text{ gpm})^2$$
$$= 81.989 \text{ psi}$$

Step 6)

- Check for convergence in the inner iteration loop

$$E_1 = DP_{1A} - DP_{1B}$$
$$= 82.076 \text{ psi} - 81.989 \text{ psi}$$
$$= 0.087 \text{ psi}$$

The magnitude of $E_1 \leq 0.1$ psi, therefore the convergence criteria is met. Go to Step 7.

TABLE 3-3 (page 3 of 4)
Verification Calculations for 2 out 4 Partial Loss of Flow Transient
Time = 0.1 to 0.2 Seconds

Step 7) Update the vessel, hot leg, and steam generator flow rates based on the estimates for cold leg flow rates.

WC = 2 (WCL_{1A} + WCL_{1B})
= 2 (5389.69 lbm/sec + 4584.16 lbm/sec)
= 19947.70 lbm/sec

QCIN = WC / ((ρ_{CL}) (0.002228 ft^3/sec/gpm))
= (19947.70 lbm/sec) / ((47.892 lbm/ft^3) (0.002228 ft^3/sec/gpm))
= 186945.35 gpm

QC = WC / ((ρ_{AVG}) (0.002228 ft^3/sec/gpm))
= (19947.70 lbm/sec) / ((45.453 lbm/ft^3) (0.002228 ft^3/sec/gpm))
= 196976.80 gpm

QCOUT = WC / ((ρ_{HL}) (0.002228 ft^3/sec/gpm))
= (19947.70 lbm/sec) / ((43.014 lbm/ft^3) (0.002228 ft^3/sec/gpm))
= 208145.88 gpm

WHL_1 = WCL_{1A} + WCL_{1B}
= 5389.69 lbm/sec + 4584.16 lbm/sec
= 9973.85 lbm/sec

QHL_1 = WHL_1 / ((ρ_{HL}) (0.002228 ft^3/sec/gpm))
= (9973.85 lbm/sec) / ((43.014 lbm/ft^3) (0.002228 ft^3/sec/gpm))
= 104072.94 gpm

$QSGT_1$ = WHL_1 / ((ρ_{AVG}) (0.002228 ft^3/sec/gpm))
= (9973.85 lbm/sec) / ((45.453 lbm/ft^3) (0.002228 ft^3/sec/gpm))
= 98488.40 gpm

TABLE 3-3 (page 4 of 4)
Verification Calculations for 2 out 4 Partial Loss of Flow Transient
Time = 0.1 to 0.2 Seconds

Step 8) Calculate the pressure loss from the outlet of RCP 1A through the cold leg, vessel, hot leg and steam generator to the inlet of RCP 1A.

$$DP_{RCS\,1} = (K_{CL}\ QCL_{1A}^2) + (K_{RVI}\ QCIN^2) + (K_C\ QC^2) + ([K_{CO} + K_{RVO}]\ QCOUT^2) + ([K_{HL} + K_{SGI}]\ QHL_1^2) + (K_{SGT}\ QSGT_1^2) + (K_{SGO}\ [QCL_{1A} + QCL_{1B}]^2)$$

$$\begin{aligned} DP_{RCS\,1} = & (8.284\text{x}10^{-10}\ \text{psi/gpm}^2)\ (50511.0\ \text{gpm})^2 \\ & +(3.979\text{x}10^{-10}\ \text{psi/gpm}^2)\ (186945.35\ \text{gpm})^2 \\ & +(3.017\text{x}10^{-10}\ \text{psi/gpm}^2)\ (196976.80\ \text{gpm})^2 \\ & +(0.449\text{x}10^{-10}\ \text{psi/gpm}^2 + 0.5827\text{x}10^{-10}\ \text{psi/gpm}^2)\ (208145.88\ \text{gpm})^2 \\ & +(6.250\text{x}10^{-10}\ \text{psi/gpm}^2 + 4.756\text{x}10^{-10}\ \text{psi/gpm}^2)\ (104072.94\ \text{gpm})^2 \\ & +(38.02\text{x}10^{-10}\ \text{psi/gpm}^2)\ (98488.40\ \text{gpm})^2 \\ & +(4.143\text{x}10^{-10}\ \text{psi/gpm}^2)\ (50511.0\ \text{gpm} + 42961.7\ \text{gpm})^2 \\ = & \ 84.615\ \text{psi} \end{aligned}$$

Step 9) Check for convergence in outer iteration loop

$$\begin{aligned} E_2 &= DP_{RCP\,1A} - DP_{RCS\,1} \\ &= 84.190\ \text{psi} - 84.615\ \text{psi} \\ &= -0.425\ \text{psi} \end{aligned}$$

The magnitude of $E_2 \leq$ convergence criteria of 1.0 psi. Therefore the flow estimates of 50511.0 gpm for RCP 1A and 42961.7 gpm for RCP 1B are correct.

Go to the next time step.

TABLE 3-4 (page 1 of 5)
Verification Calculations for 2 out 4 Partial Loss of Flow Transient
Time = 3.5 to 3.6 Seconds

Values at 3.5 seconds from the previous time step calculations:

QCL_{1A} = 65792.4 gpm $\qquad$ QCL_{1B} = -4824.0 gpm
S_{1B} = 82.99 radians/second

Step 1) Increment time

$t = t + \Delta t = 3.5 + 0.1 = 3.6$ seconds

Step 2) Calculate the speed of the pump coasting down (RCP 1B)

$$\frac{dS_{1B}}{dt} = \frac{(T_m - T_h - WIND \times (S_{1B}^{t=3.5})^2 - FRICT \times (S_{1B}^{t=3.5})^{1/2})}{PUMPI / g_c}$$

T_h is the hydraulic torque for RCP 1B evaluated at a speed of 792.5 rpm (82.99 radians/sec), a flow of -4824.0 gpm and a fluid density of 47.892 lbm/ft^3. T_h is equal to 1760.33 ft-lb (see Table B-2).

$$\frac{dS_{1B}}{dt} = \frac{(0.0) - 1760.33 \text{ ft-lb} - (0.0254 \text{ ft-lb-sec}^2) \times (82.99 \text{ radians/sec})^2 - (6.3 \text{ ft-lb-sec}^{1/2} \times (82.99 \text{ radians/sec})^{1/2}}{(5000. \text{ lbm-ft}^2) / (32.174 \text{ lbm-ft/lbf-sec}^2)}$$
$$= -12.82 \text{ radians/sec}$$

$$S_{1B}^{t=3.6} = S_{1B}^{t=3.5} + \frac{dS_{1B}}{dt} \Delta t$$
$$= (82.99 \text{ radians/sec}) + (-12.82 \text{ radians/sec}^2)(0.1 \text{ sec})$$
$$= 81.71 \text{ radians/sec}$$
or
$$= 780.27 \text{ rpm}$$

TABLE 3-4 (page 2 of 5)
Verification Calculations for 2 out 4 Partial Loss of Flow Transient
Time = 3.5 to 3.6 Seconds

Step 3)

- Estimate flow through RCP 1A (unfaulted RCP)

QCL_{1A} = 65792.4 gpm

WCL_{1A} = QCL_{1A} x (ρ_{CL}) (0.002228 ft^3/sec/gpm)
= (65792.4 gpm) (47.892 lbm/ft^3) (0.002228 ft^3/sec/gpm)
= 7020.27 lbm/sec

- Calculate the pump head for RCP 1A from homologous curves

$DP_{RCP\ 1A}$ = 38.380 psi (see from Table B-2 @ flow=65792.4 gpm, speed =1753. rpm & fluid density = 47.892 lbm/ft^3)

Step 4)

- Estimate flow through RCP 1B (faulted RCP)

QCL_{1B} = -5861.9 gpm

WCL_{1B} = QCL_{1B} x (ρ_{CL}) (0.002228 ft^3/sec/gpm)
= (-5861.9 gpm) (47.892 lbm/ft^3) (0.002228 ft^3/sec/gpm)
= -625.48 lbm/sec

- Calculate the pump head for RCP 1B from homologous curves at flow = -5861.9 gpm, speed =780.27 rpm and fluid density = 47.892 lbm/ft^3.

$DP_{RCP\ 1B}$ = 34.785 psi (see Table B-2)

TABLE 3-4 (page 3 of 5)
Verification Calculations for 2 out 4 Partial Loss of Flow Transient
Time = 3.5 to 3.6 Seconds

Step 5)

- Calculate the change in pressure from the inlet of RCP 1A through the cold leg to the reactor vessel inlet.

DP_{1A} = $DP_{RCP\ 1A} - (K_{CL})\ (QCL_{1A})^2$
= 38.380 psi - (8.284×10^{-10} psi/gpm^2) (65792.4 gpm)^2
= 34.794 psi

- Calculate the change in pressure from the inlet of RCP 1B through the cold leg to the reactor vessel inlet.

DP_{1B} = $DP_{RCP\ 1B} - (K_{CL})\ (QCL_{1B})^2$
= 34.785 psi - (8.284×10^{-10} psi/gpm^2) (-5861.9 gpm) (|-5861.9 gpm|)
= 34.813 psi

Step 6)

- Check for convergence in the inner iteration loop

E_1 = $DP_{1A} - DP_{1B}$
= 34.794 psi - 34.813 psi
= -0.019 psi

The magnitude of $E_1 \leq 0.1$ psi, therefore the convergence criteria is met. Go to Step 7.

TABLE 3-4 (page 4 of 5)
Verification Calculations for 2 out 4 Partial Loss of Flow Transient
Time = 3.5 to 3.6 Seconds

Step 7) Update the vessel, hot leg, and steam generator flow rates based on the estimates for cold leg flow rates.

$WC = 2\,(WCL_{1A} + WCL_{1B})$
= 2 (7020.27 lbm/sec + (-625.48 lbm/sec))
= 12789.58 lbm/sec

$QCIN = WC\,/\,(\,(\rho_{CL})\,(0.002228\ ft^3/sec/gpm)\,)$
= (12789.58 lbm/sec) / ((47.892 lbm/ft^3) (0.002228 ft^3/sec/gpm))
= 119861.06 gpm

$QC = WC\,/\,(\,(\rho_{AVG})\,(0.002228\ ft^3/sec/gpm)\,)$
= (12789.58 lbm/sec) / ((45.453 lbm/ft^3) (0.002228 ft^3/sec/gpm))
= 126292.79 gpm

$QCOUT = WC\,/\,(\,(\rho_{HL})\,(0.002228\ ft^3/sec/gpm)\,)$
= (12789.58 lbm/sec) / ((43.014 lbm/ft^3) (0.002228 ft^3/sec/gpm))
= 133453.90 gpm

$WHL_1 = WCL_{1A} + WCL_{1B}$
= 7020.27 lbm/sec + (-625.48 lbm/sec)
= 6394.79 lbm/sec

$QHL_1 = WHL_1\,/\,(\,(\rho_{HL})\,(0.002228\ ft^3/sec/gpm)\,)$
= (6394.79 lbm/sec) / ((43.014 lbm/ft^3) (0.002228 ft^3/sec/gpm))
= 66726.95 gpm

$QSGT_1 = WHL_1\,/\,(\,(\rho_{AVG})\,(0.002228\ ft^3/sec/gpm)\,)$
= (6394.79 lbm/sec) / ((45.453 lbm/ft^3) (0.002228 ft^3/sec/gpm))
= 63146.39 gpm

TABLE 3-4 (page 5 of 5)
Verification Calculations for 2 out 4 Partial Loss of Flow Transient
Time = 3.5 to 3.6 Seconds

Step 8) Calculate the pressure loss from the outlet of RCP 1A through the cold leg, vessel, hot leg and steam generator to the inlet of RCP 1A.

$$DP_{RCS\ 1} = (K_{CL}\ QCL_{1A}^2) + (K_{RVI}\ QCIN^2) + (K_C\ QC^2) + ([K_{CO} + K_{RVO}]\ QCOUT^2)$$
$$+ ([K_{HL} + K_{SGI}]\ QHL_1^2) + (K_{SGT}\ QSGT_1^2) + (K_{SGO}\ [QCL_{1A} + QCL_{1B}]^2)$$

$$\begin{aligned} DP_{RCS\ 1} = {} & (8.284\text{x}10^{-10}\ psi/gpm^2)\ (65792.4\ gpm)^2 \\ & +(3.979\text{x}10^{-10}\ psi/gpm^2)\ (119861.06\ gpm)^2 \\ & +(3.017\text{x}10^{-10}\ psi/gpm^2)\ (126292.79\ gpm)^2 \\ & +(0.449\text{x}10^{-10}\ psi/gpm^2 + 0.5827\text{x}10^{-10}\ psi/gpm^2)\ (133453.90\ gpm)^2 \\ & +(6.250\text{x}10^{-10}\ psi/gpm^2 + 4.756\text{x}10^{-10}\ psi/gpm^2)\ (66726.95\ gpm)^2 \\ & +(38.02\text{x}10^{-10}\ psi/gpm^2)\ (63146.39\ gpm)^2 \\ & +(4.143\text{x}10^{-10}\ psi/gpm^2)\ (65792.4\ gpm + (-5861.9\ gpm))^2 \\ = {} & 37.501\ psi \end{aligned}$$

Step 9) Check for convergence in outer iteration loop

$$\begin{aligned} E_2 &= DP_{RCP\ 1A} - DP_{RCS\ 1} \\ &= 38.380\ psi - 37.501\ psi \\ &= 0.879\ psi \end{aligned}$$

The magnitude of $E_2 \leq$ convergence criteria of 1.0 psi. Therefore the flow estimates of 65792.4 gpm for RCP 1A and -5861.9 gpm for RCP 1B are correct.

Go to the next time step.

4. Locked Rotor or Broken Shaft Followed by a Loss of AC Power Methodology

4.1 Methods Used for Locked Rotor or Broken Shaft

In the locked rotor/broken shaft loss of flow analysis presented in the SSAR, one of the four RCPs is assumed to seize at the start of the transient. The major phenomenon associated with this event is the net flow delivered to the reactor core. The actual flow in the cold legs is important only for predicting when a low flow reactor trip will occur.

The duration of the event is very short (less than 10 seconds).

The net flow loop flows for this event are calculated using a small auxiliary code (~350 line) and hand calculations. The loop flows are then input to LOFTRAN as the transient forcing functions. Section 4.2 summarizes the calculational procedure used in this code. Section 4.3 summarizes results from the code and performs hand calculations which illustrate how the code works and also verify the code.

4.2 Calculational Procedure

The following procedure summarizes the calculational steps performed by the auxiliary code for calculating the transient loop flow rates during a locked rotor or a broken shaft followed by a loss of ac power.

<u>Procedure for calculating flow during a locked rotor of broken shaft followed by a loss of AC power</u>

<u>Assumptions</u>

- The inertia of the RCS fluid is conservatively ignored.
- Referring to Figure 2-1, RCPs 1B is faulted reactor coolant pump. During the first time step, the RCP shaft is assumed to seize or break. Flow through this RCP is calculated using the RCP pressure loss coefficient (K_{PUMP}). During the first time step, RCS flow rates are stepped from the nominal full flow value to the faulted shaft steady state flow rates.
- Referring to Figure 2-1, RCPs 1A, 2A & 2B continue to run at nominal speed until reactor trip occurs. Following reactor trip, ac power is assumed to be lost and these RCPs begin coasting down.
- Fluid density in each region remains constant over the transient period.
- Mass flow rate is uniform through the RCS loop.
- The flows in cold legs 2A and 2B are symmetric and equal.

Step 1) Set Initial Conditions

- Initialize time (t = 0.0 seconds)
- Reactor coolant pump speeds are assumed to be at nominal value

  $S_{1A} = S_{1B} = S_{2A} = S_{2B}$ = nominal operating speed

- Cold leg flow rates are assumed to be at the nominal full flow value

  $QCL_{1A} = QCL_{1B} = QCL_{2A} = QCL_{2B}$ = nominal full flow value

- Set system fluid densities

<u>Start of Transient Calculations</u>

Step 2) Increment time

$t = t + \Delta t$

Step 3) Calculate speed of RCP's

For RCP1B

If t = 0.0, S_{1B} = nominal operating speed
If t > 0.0, S_{1B} = 0.0

For RCP's 1A, 2A, 2B

RCP's 1A, 2A & 2B are assumed to run at the nominal operating speed until the time at which AC power is lost. When AC power is lost these RCP's are assumed to coast down.

TPC = time at which ac power is lost

If t < TPC, $S_{1A} = S_{2A} = S_{2B}$ = nominal operating speed
If t ≥ TPC, RCP's 1A, 2A & 2B are coasting down and speed is calculated using the following:

The change in RCP speed is calculated based on the following

$$\frac{dS_i}{dt} = \frac{(T_m - T_h - WIND \times (S_i^{@t-\Delta t})^2 - FRICT \times (S_i^{@t-\Delta t})^{1/2})}{PUMPI / g_c}$$

where i = RCP number (1A, 2A or 2B)
S_i = RCP speed, radians/sec
dS/dt = transient change in RCP speed with respect to time, radians/sec²

T_m = torque supplied by the motor = 0.0 ft-lb for pumps coasting down
T_h = hydraulic torque on RCP impeller, ft-lb
WIND = RCP windage loss term, ft-lb-sec^2
FRICT = RCP friction loss term, ft-lb-sec$^{1/2}$
PUMPI = RCP rotating inertia, lbm-ft^2
g_c = 32.174 lbm-ft / lbf-sec^2

The speed of the reactor coolant pumps coasting down at time equal to t is calculated using

$$S_1^t = S_1^{t-\Delta t} + \frac{dS_1}{dt}\Delta t$$

Start of Outer Iteration Loop

Step 4) Estimate flow and hydraulic conditions in cold leg 2A

- Estimate flow through RCP 2A
- Calculate pump head and hydraulic torque for RCP 2A (See Appendix B).

Start of Inner Iteration Loop

Step 5) Estimate flow & hydraulic conditions in cold leg 1A

- Estimate flow through RCP 1A (QCL_{1A})
- Calculate pump head ($DP_{RCP\ 1A}$) and hydraulic torque ($T_{h\ RCP\ 1A}$) for RCP 1A (see Appendix B)
- Calculate the change in pressure from the inlet of RCP 1A through cold leg 1A to the reactor vessel inlet.

$$DP_{1A} = DP_{RCP\ 1A} - (K_{CL} \times QCL_{1A}^2)$$

Step 6) Calculate the flow through the faulted cold leg (RCP 1B)

$$QCL_{1B} = -\sqrt{\frac{DP_{1A}}{K_{CL} + K_{PUMP}}}$$

Step 7) Update the vessel, hot leg and steam generator flow rates based on the estimates for the cold leg flow rates

$WCL_{1A} = QCL_{1A} \times \rho_{CL} \times (0.002228\ ft^3/sec/gpm)$

$WCL_{1B} = QCL_{1B} \times \rho_{CL} \times (0.002228\ ft^3/sec/gpm)$

$WCL_{2A} = QCL_{2A} \times \rho_{CL} \times (0.002228\ ft^3/sec/gpm)$

$WC = WCL_{1A} + WCL_{1B} + 2 \times (WCL_{2A})$

$QCIN = WC / [(\rho_{CL}) (0.002228\ ft^3/sec/gpm)]$

$QC = WC / [(\rho_{AVG}) (0.002228\ ft^3/sec/gpm)]$

$QCOUT = WC / [(\rho_{HL}) (0.002228\ ft^3/sec/gpm)]$

$WHL_1 = WCL_{1A} + WCL_{1B}$

$QHL_1 = WHL_1 / [(\rho_{HL}) (0.002228\ ft^3/sec/gpm)]$

$WHL_2 = 2 \times WCL_{2A}$

$QHL_2 = WHL_2 / [(\rho_{HL}) (0.002228\ ft^3/sec/gpm)]$

$QSGT_1 = WHL_1 / [(\rho_{AVG}) (0.002228\ ft^3/sec/gpm)]$

$QSGT_2 = WHL_2 / [(\rho_{AVG}) (0.002228\ ft^3/sec/gpm)]$

Step 8) Calculate the pressure loss from the outlet of RCP 1A through the cold leg, vessel, hot leg and steam generator to the inlet of RCP 1A.

$$DP_{RCS\ 1} = (K_{CL}\ QCL_{1A}^2) + (K_{RVI}\ QCIN^2) + (K_C\ QC^2) + ([K_{CO} + K_{RVO}]\ QCOUT^2) + ([K_{HL} + K_{SGI}]\ QHL_1^2) + (K_{SGT}\ QSGT_1^2) + (K_{SGO}\ [QCL_{1A} + QCL_{1B}]^2)$$

Step 9) Check for convergence in inner iteration loop

$E_1 = DP_{RCP\ 1A} - DP_{RCS\ 1}$

- Convergence if the absolute value of $E_1 \leq$ convergence criteria (0.2 psi). Go to Step 10.

- If the E_1 is negative and the magnitude of E_1 is greater than the convergence criteria then;

  Pressure drop is higher than pump head. Reduce the estimate for QCL_{1A} to decrease the pressure drop and increase the pump head. Go to Step 5.

- If the E_1 is positive and the magnitude of E_1 is greater than the convergence criteria then;

  Pressure drop is lower than pump head. Increase the estimate for QCL_{1A} to increase the pressure drop and decrease the pump head. Go to Step 5.

End of Inner Iteration Loop

Step 10) Calculate the pressure loss from the outlet of RCP 2A through the cold leg, vessel, hot leg and steam generator to the inlet of RCP 2A.

$$DP_{RCS\,2} = (K_{CL}\ QCL_{2A}^2) + (K_{RVI}\ QCIN^2) + (K_C\ QC^2) + ([K_{CO} + K_{RVO}]\ QCOUT^2) + ([K_{HL} + K_{SGI}]\ QHL_2^2) + (K_{SGT}\ QSGT_2^2) + (K_{SGO}\ [2 \times QCL_{2A}]^2)$$

Step 11) Check for convergence in outer iteration loop

$E_2 = DP_{RCP\,2A} - DP_{RCS\,2}$

- Convergence if the absolute value of $E_2 \leq$ convergence criteria (0.2 psi). Go to Step 2 and start the next time step.

- If the E_2 is negative and the magnitude of E_2 is greater than the convergence criteria then;

  Pressure drop is higher than pump head. Reduce the estimate for QCL_{2A} to decrease the pressure drop and increase the pump head. Go to Step 4.

- If the E_2 is positive and the magnitude of E_2 is greater than the convergence criteria then;

  Pressure drop is lower than pump head. Increase the estimate for QCL_{2A} to increase the pressure drop and decrease the pump head. Go to Step 4.

End of Outer Iteration Loop

4.3 Results and Verification of the Locked Rotor/Broken Shaft Auxiliary Code

A small auxiliary code was written to perform the calculations outlined in Section 4.2. The code was used to calculate the RCS transient flow distribution for a broken reactor coolant pump shaft event.

In the transient analyzed, the shaft is assumed to break in RCP 1B (Refer to Figure 2-1). Figure 4-1 shows the calculated cold leg flow rates and the reactor coolant pumps speeds. The calculations were performed assuming a 1/10 second time step size. AC power was assumed to be lost to the unaffected reactor coolant pumps at the time of reactor trip. Reactor trip occurs at 1.45 seconds. This is between the time steps used in the auxiliary code. Therefore in the auxiliary code calculation the coastdown of the unfaulted reactor coolant pumps is conservatively assumed to start at 1.4 seconds.

In the auxiliary code calculations, the RCP shaft break is assumed to occur during the first time step executed. Flow rate is ramped to the steady state faulted conditions over this first time step. Flow then remains constant at this condition until AC power is lost and the other RCP's being coasting down.

The results from the auxiliary code calculation are used to develop an RCS flow forcing function for input to the LOFTRAN SSAR analysis. Tables 4-1 & 4-2 illustrate the development of the RCS flow which is input to LOFTRAN. Table 4-1 summarized selected time step results for reactor coolant Loop 1 as calculated by the auxiliary code. The flow rates of cold legs 1A and 1B are summed to obtained the net cold leg flow rate for input to LOFTRAN. As a further conservatism the flow rates are reduced by ~5% following the loss of offsite power. Similarly conservative flow rates input to LOFTRAN for RCS Loop 2 are developed in Table 4-2.

Hand calculations that illustrate the locked rotor/broken shaft flow calculation procedure outlined in Section 4.2 are shown in Table 4-3 through 4-6. Variable definitions are summarized in Section 2. Plant design parameters used in the calculations are summarized in Appendix A. Hand calculations are shown for the following time periods:

Table 4-3	-	Time = 0.0 to 0.1 seconds	(Broken shaft occurs)
Table 4-4	-	Time = 0.1 to 1.4 seconds	
Table 4-5	-	Time = 1.4 to 1.5 seconds	(other RCPs' begin coasting down)
Table 4-6	-	Time = 1.5 to 1.6 seconds	

These time steps illustrate the initial change in flow from normal steady state flows to the broken shaft faulted flow rates and the first two time steps of the period where AC power is assumed lost and the other RCP's begin coasting down. The procedure outlined in Section 4.2 uses an iterative approach to calculate the system flow rates. The procedure iterates on the flow rates in cold leg 1A and cold leg 2A until a pressure balance around the RCS loop is obtained.

In the hand calculations shown in Table 4-3 through 4-6, the final flow rates from the auxiliary code are used as the estimates for cold leg 1A & 2A flow rates. Tables 4-3 through 4-6 perform one iteration and demonstrate that a pressure balance around to RCS loop is obtained from the auxiliary code.

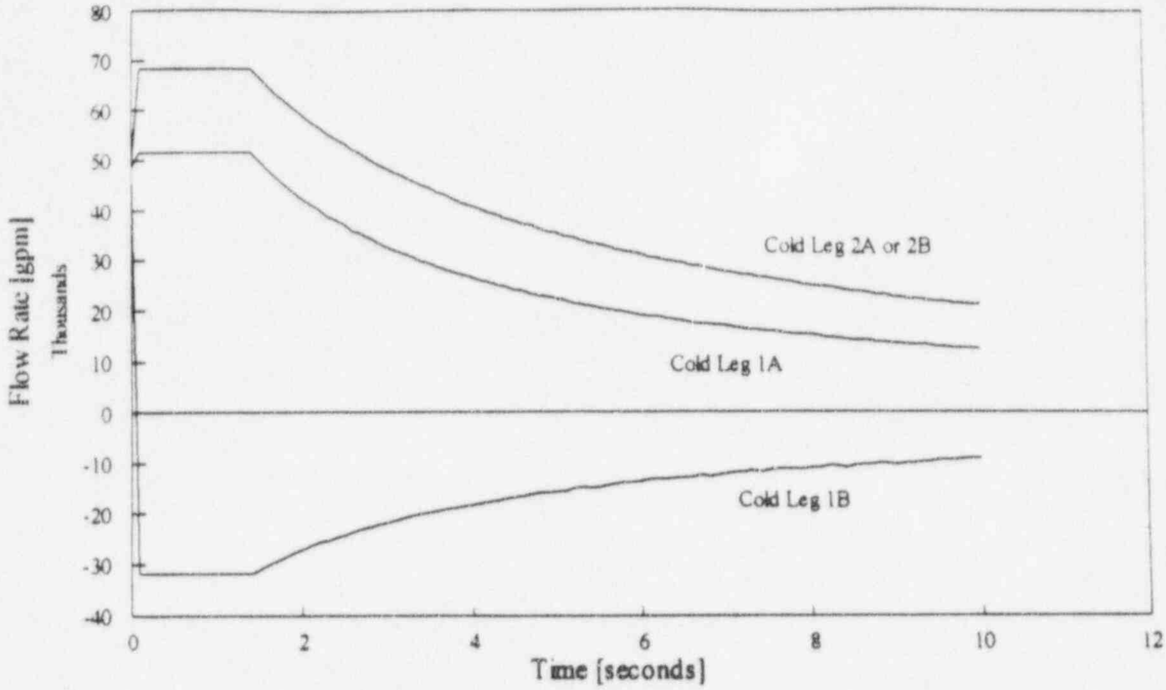
Comparison of the auxiliary code calculated values presented in Tables 4-1 and 4-2 compare within the round off accuracy expected to the hand calculations of Table 4-3 through 4-6. Tables 4-3 through 4-6 verify that the auxiliary code is performing correctly.

Table 4-1 Comparison of Loop 1 Auxiliary Code Calculated Flows to LOFTRAN SSAR Analysis Flows							
Time (sec)	Auxiliary Code Calculated Values						Flow Rate Used as input to LOFTRAN SSAR Analysis for Loop 1 (fraction of initial)
	RCP 1A Speed (radians/sec)	RCP 1B Speed (radians/sec)	Cold Leg 1A Flow (gpm)	Cold Leg 1B Flow (gpm)	Loop 1 Net Flow		
					(gpm)	(fraction)	
0.0	183.57	183.57	48300.0	48300.0	96600.0	1.0	1.0
0.01							0.3771
0.1	183.57	0.0	68204.9	-31780.0	36424.9	0.3771	
1.4	183.57	0.0	68204.9	-31780.0	36424.9	0.3771	
1.45							0.3771
1.5	178.85	0.0	66473.1	-30895.6	35577.5	0.3683	0.3499
1.6	174.37	0.0	64817.8	-30091.0	34726.8	0.3595	
2.0	158.51	0.0	59010.3	-27091.4	31918.9	0.3304	0.3159
2.5	142.38	0.0	53096.6	-24062.6	29033.9	0.3006	0.2855
3.0	129.25	0.0	48253.8	-21688.9	26564.9	0.2750	0.2612
3.5	118.36	0.0	44203.1	-19813.8	24389.3	0.2525	0.2395
4.0	109.15	0.0	40774.9	-18241.1	22533.8	0.2333	0.2216
6.0	83.22	0.0	31206.8	-13586.8	17620.0	0.1824	0.1733
8.0	67.17	0.0	25242.2	-10843.6	14398.6	0.1491	0.1416
10.0	56.21	0.0	21155.4	-8996.4	12159.0	0.1259	0.1196

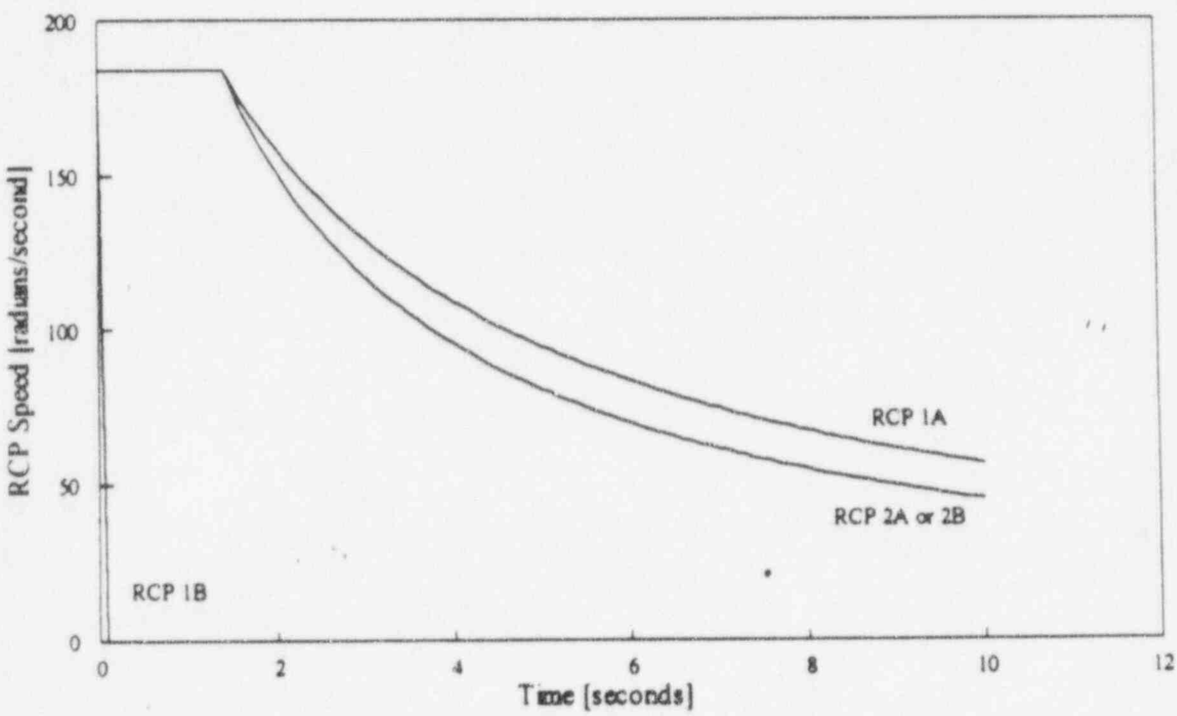
Table 4-2
Comparison of Loop 2 Auxiliary Code Calculated Flows to LOFTRAN SSAR Analysis Flows

Time (sec)	Auxiliary Code Calculated Values				Flow Rate Used as input to LOFTRAN SSAR Analysis for Loop 2 (fraction of initial)
	RCP 2A or 2B Speed (radians/sec)	Cold Leg 2A or 2B Flow (gpm)	Loop 2 Net Flow		
			(gpm)	(fraction of initial)	
0.0	183.57	48300.0	96600.0	1.0	1.0
0.01					1.0625
0.1	183.57	51318.8	102637.6	1.0625	
1.4	183.57	51318.8	102637.6	1.0625	
1.45					1.0625
1.5	177.28	49514.6	99029.2	1.0251	0.9739
1.6	171.40	47870.5	95741.0	.9911	
2.0	151.35	42203.8	84407.6	.8738	0.8301
2.5	132.07	36814.4	73628.8	.7622	0.7241
3.0	117.15	32632.4	65264.8	0.6756	0.6418
3.5	105.25	29274.2	58548.4	0.6061	0.5758
4.0	95.54	26524.9	53049.8	0.5492	0.5217
6.0	69.69	19280.5	38561.0	0.3992	0.3792
8.0	54.71	15227.7	30455.4	0.3153	0.2995

10.0	44.92	12408.6	24817.2	0.2569	0.2441



80
70
60
50
40
30
20
10
0
-10
-20
-30
-40
Flow Rate [gpm]
Thousands
Cold Leg 2A or 2B
Cold Leg 1A
Cold Leg 1B
0
2
4
6
8
10
12
Time [seconds]



200
150
100
50
0
RCP Speed [radians/second]
RCP 1A
RCP 2A or 2B
RCP 1B
0
2
4
6
8
10
12
Time [seconds]

Figure 4-1

Table 4-3 (page 1 of 6)
Verification Calculations for Broken RCP Shaft Transient
Time = 0.0 to 0.1 Seconds

Step 1) Set Initial Conditions

-Initialize time

$t = 0.0$ seconds

-Reactor coolant pump speeds are assumed to be at nominal value

$S_{1A} = S_{1B} = S_{2A} = S_{2B} = 1753.$ rpm (183.57 radians/sec)

-Cold leg flow rates are assumed to be at the nominal full flow value

$QCL_{1A} = QCL_{1B} = QCL_{2A} = QCL_{2B} = 48300.$ gpm

-Set system fluid densities

$\rho_{HL} = 43.014$ lbm/ft^3
$\rho_{CL} = 47.892$ lbm/ft^3
$\rho_{AVG} = (43.014$ lbm/ft$^3 + 47.892$ lbm/ft$^3) / 2 = 45.453$ lbm/ft^3

Step 2) Increment time

$t = t + \Delta t = 0.0 + 0.1 = 0.1$ seconds

Step 3) Calculate speed of RCP's

For RCP1B

$S_{1B} = 0.0$

For RCP's 1A, 2A, 2B

$t <$ TPC,therefore RCP's 1A, 2A & 2B are at nominal operating speed

$S_{1A} = S_{2A} = S_{2B} = 1753.$ rpm (183.57 radians/sec)

Table 4-3 (page 2 of 6)
Verification Calculations for Broken RCP Shaft Transient
Time = 0.0 to 0.1 Seconds

Step 4) Estimate flow and hydraulic conditions in cold leg 2A

- Estimate flow through RCP 2A

QCL_{2A} = 51318.8 gpm

- Calculate pump head and hydraulic torque for RCP 2A

$DP_{RCP\ 2A}$ = 82.044 psi
$T_{h\ RCP\ 2A}$ = 8846.70 ft-lb

Pump head and hydraulic torque at 1753 rpm, 51318.8 gpm & 47.892 lbm/ft^3 (See Table B-2)

Step 5) Estimate flow & hydraulic conditions in cold leg 1A

- Estimate flow through RCP 1A

QCL_{1A} = 68204.9 gpm

- Calculate pump head ($DP_{RCP\ 1A}$) and hydraulic torque ($T_{h\ RCP\ 1A}$) for RCP 1A

$DP_{RCP\ 1A}$ = 28.274 psi
$T_{h\ RCP\ 1A}$ = 6398.14 ft-lb

Pump head and hydraulic torque at 1753 rpm, 68204.9 gpm & 47.892 lbm/ft^3 (See Table B-2)

- Calculate the change in pressure from the inlet of RCP 1A through cold leg 1A to the reactor vessel inlet.

$$\begin{aligned} DP_{1A} &= DP_{RCP\ 1A} - (K_{CL} \times QCL_{1A}^2) \\ &= 28.274\ \text{psi} - (8.284\times10^{-10}\ \frac{\text{psi}}{\text{gpm}^2})(68204.9\ \text{gpm})^2 \\ &= 24.420\ \text{psi} \end{aligned}$$

Table 4-3 (page 3 of 6)
Verification Calculations for Broken RCP Shaft Transient
Time = 0.0 to 0.1 Seconds

Step 6) Calculate the flow through the faulted cold leg (RCP 1B)

$$QCL_{1B} = -\sqrt{\frac{DP_{1A}}{K_{CL} + K_{PUMP}}}$$

$$= -\sqrt{\frac{24.420 \text{ psi}}{8.284\times10^{-10} \text{ psi/gpm}^2 + 233.5\times10^{-10} \text{ psi/gpm}^2}}$$

$$= -31780.4 \text{ gpm}$$

Step 7) Update the vessel, hot leg and steam generator flow rates based on the estimates for the cold leg flow rates

WCL_{1A} = $QCL_{1A} \times \rho_{CL} \times$ (0.002228 ft^3/sec/gpm)
= (68204.9 gpm) (47.892 lbm/ft^3) (0.002228 ft^3/sec/gpm)
= 7277.69 lbm/sec

WCL_{1B} = $QCL_{1B} \times \rho_{CL} \times$ (0.002228 ft^3/sec/gpm)
= (-31780.4 gpm) (47.892 lbm/ft^3) (0.002228 ft^3/sec/gpm)
= -3391.08 lbm/sec

WCL_{2A} = $QCL_{2A} \times \rho_{CL} \times$ (0.002228 ft^3/sec/gpm)
= (51318.8 gpm) (47.892 lbm/ft^3) (0.002228 ft^3/sec/gpm)
= 5475.89 lbm/sec

WC = $WCL_{1A} + WCL_{1B} + 2 \times (WCL_{2A})$
= 7277.69 lbm/sec + (-3391.08 lbm/sec) + 2x(5475.89 lbm/sec)
= 14838.39 lbm/sec

QCIN = WC / [(ρ_{CL}) (0.002228 ft^3/sec/gpm)]
= (14838.39 lbm/sec) / ((47.892 lbm/ft^3) (0.002228 ft^3/sec/gpm))
= 139062.05 gpm

QC = WC / [(ρ_{AVG}) (0.002228 ft^3/sec/gpm)]
= (14838.39 lbm/sec) / ((45.453 lbm/ft^3) (0.002228 ft^3/sec/gpm))
= 146524.09 gpm

QCOUT = WC / [(ρ_{HL}) (0.002228 ft^3/sec/gpm)]
= (14838.39 lbm/sec) / ((43.014 lbm/ft^3) (0.002228 ft^3/sec/gpm))
= 154832.37 gpm

Table 4-3 (page 4 of 6)
Verification Calculations for Broken RCP Shaft Transient
Time = 0.0 to 0.1 Seconds

$WHL_1 = WCL_{1A} + WCL_{1B}$
$= 7277.69$ lbm/sec + (-3391.08 lbm/sec)
$= 3886.61$ lbm/sec

$QHL_1 = WHL_1 / [(\rho_{HL}) (0.002228\ ft^3/sec/gpm)]$
$= (3886.61\ lbm/sec) / ((43.014\ lbm/ft^3) (0.002228\ ft^3/sec/gpm))$
$= 40555.14$ gpm

$WHL_2 = 2 \times WCL_{2A}$
$= 2 \times 5475.89$ lbm/sec
$= 10951.78$ lbm/sec

$QHL_2 = WHL_2 / [(\rho_{HL}) (0.002228\ ft^3/sec/gpm)]$
$= (10951.78\ lbm/sec) / ((43.014\ lbm/ft^3) (0.002228\ ft^3/sec/gpm))$
$= 114277.23$ gpm

$QSGT_1 = WHL_1 / [(\rho_{AVG}) (0.002228\ ft^3/sec/gpm)]$
$= (3886.61\ lbm/sec) / ((45.453\ lbm/ft^3) (0.002228\ ft^3/sec/gpm))$
$= 38378.96$ gpm

$QSGT_2 = WHL_2 / [(\rho_{AVG}) (0.002228\ ft^3/sec/gpm)]$
$= (10951.78\ lbm/sec) / ((45.453\ lbm/ft^3) (0.002228\ ft^3/sec/gpm))$
$= 108145.13$ gpm

Table 4-3 (page 5 of 6)
Verification Calculations for Broken RCP Shaft Transient
Time = 0.0 to 0.1 Seconds

Step 8) Calculate the pressure loss from the outlet of RCP 1A through the cold leg, vessel, hot leg and steam generator to the inlet of RCP 1A.

$$DP_{RCS\ 1} = (K_{CL}\ QCL_{1A}^2) + (K_{RVI}\ QCIN^2) + (K_C\ QC^2) + ([K_{CO} + K_{RVO}]\ QCOUT^2) + ([K_{HL} + K_{SGI}]\ QHL_1^2) + (K_{SGT}\ QSGT_1^2) + (K_{SGO}\ [QCL_{1A} + QCL_{1B}]^2)$$

$$\begin{aligned} DP_{RCS\ 1} = & (8.284\times10^{-10}\ psi/gpm^2)\ (68204.9\ gpm)^2 \\ & +(3.979\times10^{-10}\ psi/gpm^2)\ (139062.05\ gpm)^2 \\ & +(3.017\times10^{-10}\ psi/gpm^2)\ (146524.09\ gpm)^2 \\ & +(0.449\times10^{-10}\ psi/gpm^2 + 0.5827\times10^{-10}\ psi/gpm^2)\ (154832.37\ gpm)^2 \\ & +(6.250\times10^{-10}\ psi/gpm^2 + 4.756\times10^{-10}\ psi/gpm^2)\ (40555.14\ gpm)^2 \\ & +(38.02\times10^{-10}\ psi/gpm^2)\ (38378.96\ gpm)^2 \\ & +(4.143\times10^{-10}\ psi/gpm^2)\ (\ 65204.9\ gpm + [-31780.4\ gpm]\ )^2 \\ = & \ 28.372\ psi \end{aligned}$$

Step 9) Check for convergence in inner iteration loop

$$\begin{aligned} E_1 &= DP_{RCP\ 1A} - DP_{RCS\ 1} \\ &= 28.274\ psi - 28.372\ psi \\ &= -0.098\ psi \end{aligned}$$

The magnitude of $E_1 \leq 0.2$ psi, therefore the convergence criteria is met. Go to Step 10.

Table 4-3 (page 6 of 6)
Verification Calculations for Broken RCP Shaft Transient
Time = 0.0 to 0.1 Seconds

Step 10) Calculate the pressure loss from the outlet of RCP 2A through the cold leg, vessel, hot leg and steam generator to the inlet of RCP 2A.

$$DP_{RCS\,2} = (K_{CL}\ QCL_{2A}^2) + (K_{RVI}\ QCIN^2) + (K_C\ QC^2) + ([K_{CO} + K_{RVO}]\ QCOUT^2) + ([K_{HL} + K_{SGI}]\ QHL_2^2) + (K_{SGT}\ QSGT_2^2) + (K_{SGO}\ [2 \times QCL_{2A}]^2)$$

$$\begin{aligned} DP_{RCS\,2} = {} & (8.284\text{x}10^{-10}\ \text{psi/gpm}^2)\ (51318.8\ \text{gpm})^2 \\ & +(3.979\text{x}10^{-10}\ \text{psi/gpm}^2)\ (139062.05\ \text{gpm})^2 \\ & +(3.017\text{x}10^{-10}\ \text{psi/gpm}^2)\ (146524.09\ \text{gpm})^2 \\ & +(0.449\text{x}10^{-10}\ \text{psi/gpm}^2 + 0.5827\text{x}10^{-10}\ \text{psi/gpm}^2)\ (154832.37\ \text{gpm})^2 \\ & +(6.250\text{x}10^{-10}\ \text{psi/gpm}^2 + 4.756\text{x}10^{-10}\ \text{psi/gpm}^2)\ (114277.23\ \text{gpm})^2 \\ & +(38.02\text{x}10^{-10}\ \text{psi/gpm}^2)\ (108145.13\ \text{gpm})^2 \\ & +(4.143\text{x}10^{-10}\ \text{psi/gpm}^2)\ (2 \text{ x } 51318.8\ \text{gpm})^2 \\ = {} & 82.030\ \text{psi} \end{aligned}$$

Step 11) Check for convergence in outer iteration loop

$$\begin{aligned} E_2 &= DP_{RCP\,2A} - DP_{RCS\,2} \\ &= 82.044\ \text{psi} - 82.030\ \text{psi} \\ &= 0.014\ \text{psi} \end{aligned}$$

The magnitude of $E_2 \leq$ convergence criteria of 0.2 psi. Therefore the flow estimates of 68204.9 gpm for RCP 1A and 51318.8 gpm for RCP 2A are correct. Go to Step 2 and start the next time step.

Table 4-4
Verification Calculations for Broken RCP Shaft Transient
Time = 0.1 to 1.4 Seconds

AC power is assumed to be lost at reactor trip at 1.45 seconds. At this time the three unfaulted ractor coolant pumps will begin coasting down. Between 0.1 seconds and 1.45 seconds RCS flow rates are assumed to remain constant at the values calculated for 0.1 seconds.

A 1/10 seconds time step size is being used in the calculations. For simplicity the coastdown of the three unfaulted RCP's will conservatively be assumed to start at 1.4 seconds.

Therefore the following conditions are assumed to occur between 0.1 and 1.4 seconds.

Time (sec.)	QCL_{1A} (gpm)	QCL_{1B} (gpm)	QCL_{2A} (gpm)	S_{1A} (rpm)	S_{1B} (rpm)	S_{2A} (rpm)
0.1	68204.9	-31780.4	51318.8	1753.	0.0	1753.
1.4	68204.9	-31780.4	51318.8	1753.	0.0	1753.

Table 4-5 (page 1 of 6)
Verification Calculations for Broken RCP Shaft Transient
Time = 1.4 to 1.5 Seconds

Step 2) Increment time

$t = t + \Delta t = 1.4 + 0.1 = 1.5$ seconds

Step 3) Calculate speed of RCP's

For RCP1B

$S_{1B} = 0.0$

For RCP's 1A, 2A, 2B

$t > TPC$, Therefore the change in RCP speed is calculated based on the following

$$\frac{dS_1}{dt} = \frac{(T_m - T_h - WIND \times (S_1^{@t-\Delta t})^2 - FRICT \times (S_1^{@t-\Delta t})^{1/2})}{PUMPI / g_c}$$

$$S_1^t = S_1^{t-\Delta t} + \frac{dS_1}{dt} \Delta t$$

$T_{h\ RCP\ 1A}$ = 6398.14 ft-lb, hydraulic torque at speed of 1753. rpm, flow of 68204.9 gpm and density of 47.892 lbm/ft^3 (See Table B-2).

$T_{h\ RCP\ 2A}$ = 8846.70 ft-lb, hydraulic torque at speed of 1753. rpm, flow of 51318.8 gpm and density of 47.892 lbm/ft^3 (See Table B-2).

$$\frac{dS_{1A}}{dt} = \frac{(0.0) - 6398.14 \text{ ft-lb} - (0.0254 \text{ ft-lb-sec}^2) \times (183.57 \text{ radians/sec})^2 - (6.3 \text{ ft-lb-sec}^{1/2} \times (183.57 \text{ radians/sec})^{1/2}}{(5000. \text{ lbm-ft}^2) / (32.174 \text{ lbm-ft/lbf-sec}^2)}$$

$$= -47.23 \text{ radians/sec}$$

$$\frac{dS_{2A}}{dt} = \frac{(0.0) - 8846.70 \text{ ft-lb} - (0.0254 \text{ ft-lb-sec}^2) \times (183.57 \text{ radians/sec})^2 - (6.3 \text{ ft-lb-sec}^{1/2} \times (183.57 \text{ radians/sec})^{1/2}}{(5000. \text{ lbm-ft}^2) / (32.174 \text{ lbm-ft/lbf-sec}^2)}$$

$$= -62.98 \text{ radians/sec}$$

Table 4-5 (page 2 of 6)
Verification Calculations for Broken RCP Shaft Transient
Time = 1.4 to 1.5 Seconds

$$S_{1A}^{t=1.5} = S_{1A}^{t=1.4} + \frac{dS_{1A}}{dt}\Delta t$$
$$= (183.57 \text{ radians/sec}) + (-47.23 \text{ radians/sec}^2)(0.1 \text{ sec})$$
$$= 178.847 \text{ radians/sec}$$
or
$$= 1707.86 \text{ rpm}$$

$$S_{2A}^{t=1.5} = S_{2A}^{t=1.4} + \frac{dS_{2A}}{dt}\Delta t$$
$$= (183.57 \text{ radians/sec}) + (-62.98 \text{ radians/sec}^2)(0.1 \text{ sec})$$
$$= 177.272 \text{ radians/sec}$$
or
$$= 1692.82 \text{ rpm}$$

Step 4) Estimate flow and hydraulic conditions in cold leg 2A

- Estimate flow through RCP 2A

QCL_{2A} = 49514.6 gpm

- Calculate pump head and hydraulic torque for RCP 2A

$DP_{RCP\ 2A}$ = 76.616 psi
$T_{h\ RCP\ 2A}$ = 8251.40 ft-lb

Pump head and hydraulic torque at 1692.82 rpm (177.272 radians/sec), 49514.6 gpm & 47.892 lbm/ft^3 (See Table B-2)

Table 4-5 (page 3 of 6)
Verification Calculations for Broken RCP Shaft Transient
Time = 1.4 to 1.5 Seconds

Step 5) Estimate flow & hydraulic conditions in cold leg 1A

- Estimate flow through RCP 1A

  QCL_{1A} = 66473.1 gpm

- Calculate pump head ($DP_{RCP\ 1A}$) and hydraulic torque ($T_{h\ RCP\ 1A}$) for RCP 1A

$DP_{RCP\ 1A}$	=	26.733 psi	Pump head and hydraulic torque at 1707.86 rpm (178.847 radians/sec), 66473.1 gpm & 47.892 lbm/ft^3 (See Table B-2)
$T_{h\ RCP\ 1A}$	=	6067.53 ft-lb	

- Calculate the change in pressure from the inlet of RCP 1A through cold leg 1A to the reactor vessel inlet.

$$DP_{1A} = DP_{RCP\ 1A} - (K_{CL} \times QCL_{1A}^{2})$$
$$= 26.733 \text{ psi} - (8.284\text{x}10^{-10} \frac{\text{psi}}{\text{gpm}^2}) (66473.1 \text{ gpm})^2$$
$$= 23.073 \text{ psi}$$

Step 6) Calculate the flow through the faulted cold leg (RCP 1B)

$$QCL_{1B} = -\sqrt{\frac{DP_{1A}}{K_{CL} + K_{PUMP}}}$$
$$= -\sqrt{\frac{23.073 \text{ psi}}{8.284\text{x}10^{-10} \text{ psi/gpm}^2 + 233.5\text{x}10^{-10} \text{ psi/gpm}^2}}$$
$$= -30891.45 \text{ gpm}$$

Table 4-5 (page 4 of 6)
Verification Calculations for Broken RCP Shaft Transient
Time = 1.4 to 1.5 Seconds

Step 7) Update the vessel, hot leg and steam generator flow rates based on the estimates for the cold leg flow rates

WCL_{1A} = $QCL_{1A} \times \rho_{CL} \times$ (0.002228 ft^3/sec/gpm)
= (66473.1 gpm) (47.892 lbm/ft^3) (0.002228 ft^3/sec/gpm)
= 7092.90 lbm/sec

WCL_{1B} = $QCL_{1B} \times \rho_{CL} \times$ (0.002228 ft^3/sec/gpm)
= (-30891.45 gpm) (47.892 lbm/ft^3) (0.002228 ft^3/sec/gpm)
= -3296.22 lbm/sec

WCL_{2A} = $QCL_{2A} \times \rho_{CL} \times$ (0.002228 ft^3/sec/gpm)
= (49514.6 gpm) (47.892 lbm/ft^3) (0.002228 ft^3/sec/gpm)
= 5283.37 lbm/sec

WC = $WCL_{1A} + WCL_{1B} + 2 \times (WCL_{2A})$
= 7092.90 lbm/sec + (-3296.22 lbm/sec) + 2x(5283.37 lbm/sec)
= 14363.42 lbm/sec

QCIN = WC / [(ρ_{CL}) (0.002228 ft^3/sec/gpm)]
= (14363.42 lbm/sec) / ((47.892 lbm/ft^3) (0.002228 ft^3/sec/gpm))
= 134610.74 gpm

QC = WC / [(ρ_{AVG}) (0.002228 ft^3/sec/gpm)]
= (14363.42 lbm/sec) / ((45.453 lbm/ft^3) (0.002228 ft^3/sec/gpm))
= 141833.92 gpm

QCOUT = WC / [(ρ_{HL}) (0.002228 ft^3/sec/gpm)]
= (14363.42 lbm/sec) / ((43.014 lbm/ft^3) (0.002228 ft^3/sec/gpm))
= 149876.26 gpm

WHL_1 = $WCL_{1A} + WCL_{1B}$
= 7092.90 lbm/sec + (-3296.22 lbm/sec)
= 3796.68 lbm/sec

QHL_1 = WHL_1 / [(ρ_{HL}) (0.002228 ft^3/sec/gpm)]
= (3796.68 lbm/sec) / ((43.014 lbm/ft^3) (0.002228 ft^3/sec/gpm))
= 39612.76 gpm

WHL_2 = $2 \times WCL_{2A}$
= 2 x 5283.37 lbm/sec
= 10566.74 lbm/sec

Table 4-5 (page 5 of 6)
Verification Calculations for Broken RCP Shaft Transient
Time = 1.4 to 1.5 Seconds

QHL_2 = WHL_2 / [(ρ_{HL}) (0.002228 ft^3/sec/gpm)]
= (10566.74 lbm/sec) / ((43.014 lbm/ft^3) (0.002228 ft^3/sec/gpm))
= 110259.50 gpm

$QSGT_1$ = WHL_1 / [(ρ_{AVG}) (0.002228 ft^3/sec/gpm)]
= (3796.68 lbm/sec) / ((45.453 lbm/ft^3) (0.002228 ft^3/sec/gpm))
= 37490.93 gpm

$QSGT_2$ = WHL_2 / [(ρ_{AVG}) (0.002228 ft^3/sec/gpm)]
= (10566.74 lbm/sec) / ((45.453 lbm/ft^3) (0.002228 ft^3/sec/gpm))
= 104342.99 gpm

Step 8) Calculate the pressure loss from the outlet of RCP 1A through the cold leg, vessel, hot leg and steam generator to the inlet of RCP 1A.

$$DP_{RCS\,1} = (K_{CL}\ QCL_{1A}^2) + (K_{RVI}\ QCIN^2) + (K_C\ QC^2) + ([K_{CO} + K_{RVO}]\ QCOUT^2) + ([K_{HL} + K_{SGI}]\ QHL_1^2) + (K_{SGT}\ QSGT_1^2) + (K_{SGO}\ [QCL_{1A} + QCL_{1B}]^2)$$

$$\begin{aligned} DP_{RCS\,1} &= (8.284\times10^{-10}\ psi/gpm^2)\ (66473.1\ gpm)^2 \\ &+(3.979\times10^{-10}\ psi/gpm^2)\ (134610.74\ gpm)^2 \\ &+(3.017\times10^{-10}\ psi/gpm^2)\ (141833.92\ gpm)^2 \\ &+(0.449\times10^{-10}\ psi/gpm^2 + 0.5827\times10^{-10}\ psi/gpm^2)\ (149876.26\ gpm)^2 \\ &+(6.250\times10^{-10}\ psi/gpm^2 + 4.756\times10^{-10}\ psi/gpm^2)\ (39612.76\ gpm)^2 \\ &+(38.02\times10^{-10}\ psi/gpm^2)\ (37490.93\ gpm)^2 \\ &+(4.143\times10^{-10}\ psi/gpm^2)\ (\ 66473.1\ gpm + [-30891.45\ gpm]\ )^2 \\ &= 26.853\ psi \end{aligned}$$

Step 9) Check for convergence in inner iteration loop

E_1 = $DP_{RCP\,1A}$ - $DP_{RCS\,1}$
= 26.733 psi - 26.853 psi
= -0.120 psi

The magnitude of $E_1 \leq 0.2$ psi, therefore the convergence criteria is met. Go to Step 10.

Table 4-5 (page 6 of 6)
Verification Calculations for Broken RCP Shaft Transient
Time = 1.4 to 1.5 Seconds

Step 10) Calculate the pressure loss from the outlet of RCP 2A through the cold leg, vessel, hot leg and steam generator to the inlet of RCP 2A.

$$DP_{RCS\,2} = (K_{CL}\ QCL_{2A}^2) + (K_{RVI}\ QCIN^2) + (K_C\ QC^2) + ([K_{CO} + K_{RVO}]\ QCOUT^2) + ([K_{HL} + K_{SGI}]\ QHL_2^2) + (K_{SGT}\ QSGT_2^2) + (K_{SGO}\ [2 \times QCL_{2A}]^2)$$

$$\begin{aligned} DP_{RCS\,2} = {} & (8.284\times10^{-10}\ psi/gpm^2)\ (49514.6\ gpm)^2 \\ & +(3.979\times10^{-10}\ psi/gpm^2)\ (134610.74\ gpm)^2 \\ & +(3.017\times10^{-10}\ psi/gpm^2)\ (141833.92\ gpm)^2 \\ & +(0.449\times10^{-10}\ psi/gpm^2 + 0.5827\times10^{-10}\ psi/gpm^2)\ (149876.26\ gpm)^2 \\ & +(6.250\times10^{-10}\ psi/gpm^2 + 4.756\times10^{-10}\ psi/gpm^2)\ (110259.50\ gpm)^2 \\ & +(38.02\times10^{-10}\ psi/gpm^2)\ (104342.99\ gpm)^2 \\ & +(4.143\times10^{-10}\ psi/gpm^2)\ (2 \times 49514.6\ gpm)^2 \\ = {} & 76.465\ psi \end{aligned}$$

Step 11) Check for convergence in outer iteration loop

$$\begin{aligned} E_2 &= DP_{RCP\,2A} - DP_{RCS\,2} \\ &= 76.616\ psi - 76.465\ psi \\ &= 0.151\ psi \end{aligned}$$

The magnitude of $E_2 \le$ convergence criteria of 0.2 psi. Therefore the flow estimates of 66473.1 gpm for RCP 1A and 49514.6 gpm for RCP 2A are correct. Go to Step 2 and start the next time step.

Table 4-6 (page 1 of 6)
Verification Calculations for Broken RCP Shaft Transient
Time = 1.5 to 1.6 Seconds

Step 2) Increment time

$t = t + \Delta t = 1.5 + 0.1 = 1.6$ seconds

Step 3) Calculate speed of RCP's

For RCP1B

$S_{1B} = 0.0$

For RCP's 1A, 2A, 2B

t > TPC, Therefore the change in RCP speed is calculated based on the following

$$\frac{dS_l}{dt} = \frac{(T_m - T_h - WIND \times (S_l^{@t-\Delta t})^2 - FRICT \times (S_l^{@t-\Delta t})^{1/2})}{PUMPI / g_c}$$

$$S_l^t = S_l^{t-\Delta t} + \frac{dS_l}{dt} \Delta t$$

$T_{h\ RCP\ 1A}$ = 6067.53 ft-lb, hydraulic torque at speed of 1707.86 rpm (178.847 radians/sec), flow of 66473.1 gpm and density of 47.892 lbm/ft^3 (See Table B-2).

$T_{h\ RCP\ 2A}$ = 8251.40 ft-lb, hydraulic torque at speed of 1692.82 rpm (177.272 radians/sec), flow of 49514.6 gpm and density of 47.892 lbm/ft^3 (See Table B-2).

$$\frac{dS_{1A}}{dt} = \frac{(0.0) - 6067.53 \text{ ft-lb} - (0.0254 \text{ ft-lb-sec}^2) \times (178.847 \text{ radians/sec})^2 - (6.3 \text{ ft-lb-sec}^{1/2} \times (178.847 \text{ radians/sec})^{1/2}}{(5000.\ \text{lbm-ft}^2) / (32.174 \text{ lbm-ft/lbf-sec}^2)}$$

$$= -44.81 \text{ radians/sec}$$

$$\frac{dS_{2A}}{dt} = \frac{(0.0) - 8251.40 \text{ ft-lb} - (0.0254 \text{ ft-lb-sec}^2) \times (177.272 \text{ radians/sec})^2 - (6.3 \text{ ft-lb-sec}^{1/2} \times (177.272 \text{ radians/sec})^{1/2}}{(5000.\ \text{lbm-ft}^2) / (32.174 \text{ lbm-ft/lbf-sec}^2)}$$

$$= -58.77 \text{ radians/sec}$$

Table 4-6 (page 2 of 6)
Verification Calculations for Broken RCP Shaft Transient
Time = 1.5 to 1.6 Seconds

$$S_{1A}^{t=1.6} = S_{1A}^{t=1.5} + \frac{dS_{1A}}{dt}\,\Delta t$$
$$= (178.847 \text{ radians/sec}) + (-44.81 \text{ radians/sec}^2)\,(0.1 \text{ sec})$$
$$= 174.366 \text{ radians/sec}$$
or
$$= 1665.07 \text{ rpm}$$

$$S_{2A}^{t=1.6} = S_{2A}^{t=1.5} + \frac{dS_{2A}}{dt}\,\Delta t$$
$$= (177.272 \text{ radians/sec}) + (-58.77 \text{ radians/sec}^2)\,(0.1 \text{ sec})$$
$$= 171.395 \text{ radians/sec}$$
or
$$= 1636.70 \text{ rpm}$$

Step 4) Estimate flow and hydraulic conditions in cold leg 2A

- Estimate flow through RCP 2A

  QCL_{2A} = 47870.5 gpm

- Calculate pump head and hydraulic torque for RCP 2A

  $DP_{RCP\ 2A}$ = 71.627 psi
  $T_{h\ RCP\ 2A}$ = 7713.48 ft-lb

  Pump head and hydraulic torque at 1636.70 rpm (171.395 radians/sec), 47870.5 gpm & 47.892 lbm/ft^3 (See Table B-2)

Table 4-6 (page 3 of 6)
Verification Calculations for Broken RCP Shaft Transient
Time = 1.5 to 1.6 Seconds

Step 5) Estimate flow & hydraulic conditions in cold leg 1A

- Estimate flow through RCP 1A

QCL_{1A} = 64817.8 gpm

- Calculate pump head ($DP_{RCP\ 1A}$) and hydraulic torque ($T_{h\ RCP\ 1A}$) for RCP 1A

$DP_{RCP\ 1A}$ = 25.368 psi
$T_{h\ RCP\ 1A}$ = 5765.13 ft-lb

Pump head and hydraulic torque at 1665.07 rpm (174.366 radians/sec), 64817.8 gpm & 47.892 lbm/ft^3 (See Table B-2)

- Calculate the change in pressure from the inlet of RCP 1A through cold leg 1A to the reactor vessel inlet.

$$DP_{1A} = DP_{RCP\ 1A} - (K_{CL} \times QCL_{1A}^2)$$
$$= 25.368\ \text{psi} - (8.284\times10^{-10}\ \frac{\text{psi}}{\text{gpm}^2}) (64817.8\ \text{gpm})^2$$
$$= 21.888\ \text{psi}$$

Step 6) Calculate the flow through the faulted cold leg (RCP 1B)

$$QCL_{1B} = -\sqrt{\frac{DP_{1A}}{K_{CL} + K_{PUMP}}}$$
$$= -\sqrt{\frac{21.888\ \text{psi}}{8.284\times10^{-10}\ \text{psi/gpm}^2 + 233.5\times10^{-10}\ \text{psi/gpm}^2}}$$
$$= -30087.7\ \text{gpm}$$

Table 4-6 (page 4 of 6)
Verification Calculations for Broken RCP Shaft Transient
Time = 1.5 to 1.6 Seconds

Step 7) Update the vessel, hot leg and steam generator flow rates based on the estimates for the cold leg flow rates

WCL_{1A} = $QCL_{1A} \times \rho_{CL} \times (0.002228\ ft^3/sec/gpm)$
= (64817.8 gpm) (47.892 lbm/ft^3) (0.002228 ft^3/sec/gpm)
= 6916.28 lbm/sec

WCL_{1B} = $QCL_{1B} \times \rho_{CL} \times (0.002228\ ft^3/sec/gpm)$
= (-30087.7 gpm) (47.892 lbm/ft^3) (0.002228 ft^3/sec/gpm)
= -3210.46 lbm/sec

WCL_{2A} = $QCL_{2A} \times \rho_{CL} \times (0.002228\ ft^3/sec/gpm)$
= (47870.5 gpm) (47.892 lbm/ft^3) (0.002228 ft^3/sec/gpm)
= 5107.94 lbm/sec

WC = $WCL_{1A} + WCL_{1B} + 2 \times (WCL_{2A})$
= 6916.28 lbm/sec + (-3210.46 lbm/sec) + 2x(5107.94 lbm/sec)
= 13921.7 lbm/sec

QCIN = WC / [(ρ_{CL}) (0.002228 ft^3/sec/gpm)]
= (13921.7 lbm/sec) / ((47.892 lbm/ft^3) (0.002228 ft^3/sec/gpm))
= 130471.04 gpm

QC = WC / [(ρ_{AVG}) (0.002228 ft^3/sec/gpm)]
= (13921.7 lbm/sec) / ((45.453 lbm/ft^3) (0.002228 ft^3/sec/gpm))
= 137472.09 gpm

QCOUT = WC / [(ρ_{HL}) (0.002228 ft^3/sec/gpm)]
= (13921.7 lbm/sec) / ((43.014 lbm/ft^3) (0.002228 ft^3/sec/gpm))
= 145267.10 gpm

WHL_1 = $WCL_{1A} + WCL_{1B}$
= 6916.28 lbm/sec + (-3210.46 lbm/sec)
= 3705.82 lbm/sec

QHL_1 = WHL_1 / [(ρ_{HL}) (0.002228 ft^3/sec/gpm)]
= (3705.82 lbm/sec) / ((43.014 lbm/ft^3) (0.002228 ft^3/sec/gpm))
= 38668.68 gpm

WHL_2 = $2 \times WCL_{2A}$
= 2 x 5107.94 lbm/sec
= 10215.88 lbm/sec

Table 4-6 (page 5 of 6)
Verification Calculations for Broken RCP Shaft Transient
Time = 1.5 to 1.6 Seconds

$QHL_2 = WHL_2 / [(\rho_{HL}) (0.002228\ ft^3/sec/gpm)]$
$= (10215.88\ lbm/sec) / ((43.014\ lbm/ft^3) (0.002228\ ft^3/sec/gpm))$
$= 106598.42\ gpm$

$QSGT_1 = WHL_1 / [(\rho_{AVG}) (0.002228\ ft^3/sec/gpm)]$
$= (3705.82\ lbm/sec) / ((45.453\ lbm/ft^3) (0.002228\ ft^3/sec/gpm))$
$= 36593.72\ gpm$

$QSGT_2 = WHL_2 / [(\rho_{AVG}) (0.002228\ ft^3/sec/gpm)]$
$= (10215.88\ lbm/sec) / ((45.453\ lbm/ft^3) (0.002228\ ft^3/sec/gpm))$
$= 100878.37\ gpm$

Step 8) Calculate the pressure loss from the outlet of RCP 1A through the cold leg, vessel, hot leg and steam generator to the inlet of RCP 1A.

$$DP_{RCS\ 1} = (K_{CL}\ QCL_{1A}^2) + (K_{RVI}\ QCIN^2) + (K_C\ QC^2) + ([K_{CO} + K_{RVO}]\ QCOUT^2) + ([K_{HL} + K_{SGI}]\ QHL_1^2) + (K_{SGT}\ QSGT_1^2) + (K_{SGO}\ [QCL_{1A} + QCL_{1B}]^2)$$

$$\begin{aligned} DP_{RCS\ 1} = & (8.284\times10^{-10}\ psi/gpm^2)\ (64817.8\ gpm)^2 \\ & +(3.979\times10^{-10}\ psi/gpm^2)\ (130471.04\ gpm)^2 \\ & +(3.017\times10^{-10}\ psi/gpm^2)\ (137472.09\ gpm)^2 \\ & +(0.449\times10^{-10}\ psi/gpm^2 + 0.5827\times10^{-10}\ psi/gpm^2)\ (145267.10\ gpm)^2 \\ & +(6.250\times10^{-10}\ psi/gpm^2 + 4.756\times10^{-10}\ psi/gpm^2)\ (38668.68\ gpm)^2 \\ & +(38.02\times10^{-10}\ psi/gpm^2)\ (36593.72\ gpm)^2 \\ & +(4.143\times10^{-10}\ psi/gpm^2)\ (\ 64817.8\ gpm + [-30087.7\ gpm]\ )^2 \end{aligned}$$

$$= 25.369\ psi$$

Step 9) Check for convergence in inner iteration loop

$E_1 = DP_{RCP\ 1A} - DP_{RCS\ 1}$
$= 25.368\ psi - 25.369\ psi$
$= -0.001\ psi$

The magnitude of $E_1 \leq 0.2$ psi, therefore the convergence criteria is met. Go to Step 10.

Table 4-6 (page 6 of 6) Verification Calculations for Broken RCP Shaft Transient Time = 1.5 to 1.6 Seconds

Step 10) Calculate the pressure loss from the outlet of RCP 2A through the cold leg, vessel, hot leg and steam generator to the inlet of RCP 2A.

$$DP_{RCS\,2} = (K_{CL}\ QCL_{2A}^2) + (K_{RVI}\ QCIN^2) + (K_C\ QC^2) + ([K_{CO} + K_{RVO}]\ QCOUT^2) + ([K_{HL} + K_{SGI}]\ QHL_2^2) + (K_{SGT}\ QSGT_2^2) + (K_{SGO}\ [2 \times QCL_{2A}]^2)$$

$$\begin{aligned} DP_{RCS\,2} = \; & (8.284\text{x}10^{-10}\ \text{psi/gpm}^2)\ (47870.5\ \text{gpm})^2 \\ & +(3.979\text{x}10^{-10}\ \text{psi/gpm}^2)\ (130471.04\ \text{gpm})^2 \\ & +(3.017\text{x}10^{-10}\ \text{psi/gpm}^2)\ (137472.09\ \text{gpm})^2 \\ & +(0.449\text{x}10^{-10}\ \text{psi/gpm}^2 + 0.5827\text{x}10^{-10}\ \text{psi/gpm}^2)\ (145267.10\ \text{gpm})^2 \\ & +(6.250\text{x}10^{-10}\ \text{psi/gpm}^2 + 4.756\text{x}10^{-10}\ \text{psi/gpm}^2)\ (106598.42\ \text{gpm})^2 \\ & +(38.02\text{x}10^{-10}\ \text{psi/gpm}^2)\ (100878.37\ \text{gpm})^2 \\ & +(4.143\text{x}10^{-10}\ \text{psi/gpm}^2)\ (2 \times 47870.5\ \text{gpm})^2 \\ = \; & 71.545\ \text{psi} \end{aligned}$$

Step 11) Check for convergence in outer iteration loop

$$\begin{aligned} E_2 &= DP_{RCP\,2A} - DP_{RCS\,2} \\ &= 71.627\ \text{psi} - 71.545\ \text{psi} \\ &= 0.082\ \text{psi} \end{aligned}$$

The magnitude of $E_2 \leq$ convergence criteria of 0.2 psi. Therefore the flow estimates of 64817.8 gpm for RCP 1A and 47870.5 gpm for RCP 2A are correct. Go to Step 2 and start the next time step.

Appendix A Plant Design Data Used in Calculations

RCS Pressure Loss Coefficients			
Region/Description			Loss Coefficient [psi/gpm²]
K_{CL}	cold leg		8.284×10^{-10}
K_{RVI}	reactor vessel inlet region		3.979×10^{-10}
K_{C}	core active fuel		3.017×10^{-10}
K_{CO}	core outlet region		0.449×10^{-10}
K_{RVO}	reactor vessel outlet region		0.5827×10^{-10}
K_{HL}	hot leg		6.250×10^{-10}
K_{SGI}	steam generator inlet nozzle & plenum		4.756×10^{-10}
K_{SGT}	steam generator tubes		38.02×10^{-10}
K_{SGO}	steam generator outlet plenum & nozzle		4.143×10^{-10}
K_{PUMP}	non-operating reactor coolant pump	free spinning	233.5×10^{-10}
		stationary	547.1×10^{-10}

WIND = 0.0254 ft-lb-sec^2
FRICT = 6.3 ft-lb-sec$^{1/2}$
PUMPI = 5000. lb ft^2

Nominal Operating Conditions

RCS Pressure	=	2250. psia
Minimum Measured Flow	=	193200. gpm (plant total)
	=	48300. gpm (per cold leg)
Hot leg temperature	=	601.775 °F
Cold leg temperature	=	533.425 °F
Hot leg fluid density	=	43.014 lbm/ft^3
Cold leg fluid density	=	47.892 lbm/ft^3
Nominal RCP speed	=	1753. rpm

Appendix B RCP Head, Torque, Speed & Flow Characteristics

Transient operating conditions for the reactor coolant pumps are derived homologous curves for head and hydraulic torque. Table B-1 summarizes points from the pump homologous curves used in calculations in this report. The data summarized in Table B-1 is also used in the LOFTRAN code.

Pump head is interpolated from the homologous curve data given in Table B-1a as a function of speed and flow and denormalized based on the reference parameters given in Table B-1c Linear interpolation is used.

Pump hydraulic torque is interpolated from the homologous curve data given in Table B-1b as a function of speed and flow and denormalized based on the reference parameters given in Table B-1c Linear interpolation is used.

Following are several hand calculations which illustrate the how pump head and hydraulic torque are obtained from the homologous curve data.

Example 1

Given: N (speed) = 183.57 radians/sec (1753. rpm)
Q (flow) = 48300. gpm
ρ (density) = 47.892 lbm/ft^2

Then:

$\upsilon = Q/Q_R$ = (48300. gpm) / (51000. gpm) = 0.94706

$\alpha = N/N_R$ = (1753. rpm) / (1735. rpm) = 1.01037

υ/α = 0.94706 / 1.01037 = 0.93734

υ is positive and υ is less than α, therefore the HAN and BAN line segments are used to find RCP head and hydraulic torque.

Linearly interpolating from Table B-1a from the HAN line segment at υ/α = 0.93734

$$h/\alpha^2 = \frac{0.93734 - 0.75}{1.0 - 0.75}(1.0 - 1.42) + 1.42 = 1.10527$$

$$H = (h/\alpha^2)\,\alpha^2\,H_R = (1.10527)(1.01037)^2\,(240.\ \text{ft}) = 270.79\ \text{ft}$$

At a fluid density of 47.892 lbm/ft^3 the head in psi is H = 90.062 psi

Linearly interpolating from Table B-1b from the BAN line segment at υ/α = 0.93734

$$\beta/\alpha^2 = \frac{0.93734 - 0.75}{1.0 - 0.75}(1.0 - 1.06) + 1.06 = 1.01504$$

$$T_H = (\beta/\alpha^2)\ \alpha^2\ (T_R / \rho_R)\ \rho = (1.01504)(1.01037)^2\ \frac{8677\ \text{lb-ft}}{48.\ \text{lbm/ft}^3}\ (47.892\ \text{lbm/ft}^3) = 8970.89\ \text{ft-lb}$$

Example 2

Given: N (speed) = 780.27 rpm (81.71 radians/sec)
Q (flow) = -5861.9 gpm
ρ (density) = 47.892 lbm/ft^2

Then:

$\upsilon = Q/Q_R$ = (-5861.9 gpm) / (51000. gpm) = -0.11494

$\alpha = N/N_R$ = (780.27 rpm) / (1735. rpm) = 0.44972

υ/α = -0.11494 / 0.44972 = -0.25558

υ is negative and the magnitude of υ is less than α, therefore the HAD and BAD line segments are used to find RCP head and hydraulic torque.

Linearly interpolating from Table B-1a from the HAD line segment at υ/α = -0.25558

$$h/\alpha^2 = \frac{(-0.25558) - (-0.25)}{(-0.50) - (-0.25)}(2.8 - 2.14) + 2.14 = 2.15473$$

$$H = (h/\alpha^2)\ \alpha^2\ H_R = (2.15473)(0.44972)^2\ (240.\ \text{ft}) = 104.590\ \text{ft}$$

At a fluid density of 47.892 lbm/ft^3 the head in psi is H = 34.785 psi

Linearly interpolating from Table B-1b from the BAD line segment at υ/α = -0.25558

$$\beta/\alpha^2 = \frac{(-0.25558) - (-0.25)}{(-0.50) - (-0.25)} (1.57 - 0.99) + 0.99 = 1.00295$$

$$T_H = (\beta/\alpha^2)\ \alpha^2\ (T_R\ /\rho_R)\ \rho = (1.00295)(0.44972)^2\ \frac{8677\ \text{lb-ft}}{48.\ \text{lbm/ft}^3}\ (47.892\ \text{lbm/ft}^3) = 1756.12\ \text{ft-lb}$$

In Table B-2 are given the auxiliary code calculated head and hydraulic torque values for comparison to those calculated in hand calculation Examples 1 & 2. The hand calculated values compare within the expected roundoff accuracy. Table B-2 also summaries head & hydraulic torque values at various other flows and speeds used in calculation in other sections of this report.

Table B-1a RCP Homologous Curves Head - Flow - Speed Characteristics				
υ/α or α/υ	HVD ($h/υ^2$ as a function of α/υ)	HAD ($h/α^2$ as a function of υ/α)	HAN ($h/α^2$ as a function of υ/α)	HVN ($h/υ^2$ as a function of α/υ)
-1.0	4.98	4.98		
-0.75	3.98	3.64		
-0.50	3.2	2.8		
-0.25	2.64	2.14		
0.0	2.27	1.84	1.84	-1.55
0.25			1.65	-0.98
0.50			1.63	-0.45
0.75			1.42	0.18
1.0			1.00	1.00

Table B-1b RCP Homologous Curves Torque - Flow - Speed Characteristics				
υ/α or α/υ	BVD ($β/υ^2$ as a function of α/υ)	BAD ($β/α^2$ as a function of υ/α)	BAN ($β/α^2$ as a function of υ/α)	BVN ($β/υ^2$ as a function of α/υ)
-1.0	3.38	3.38		
-0.75	2.78	2.22		
-0.50	2.3	1.57		
-0.25	1.98	0.99		
0.0	1.78	0.9	0.9	-1.85
0.25			0.94	-0.95
0.50			0.98	-0.24
0.75			1.06	0.4
1.0			1.00	1.0

Table B-1c Reference Point & Definitions

Flow	Q_R = 51000. gpm	$υ = Q/Q_R$	
Head	H_R = 240 ft.	$h = H/H_R$	
Speed	N_R = 1735. rpm	$α = N/N_R$	
Torque	T_R = 8677 lb-ft	$β = (T/W) / (T_R / W_R)$	
Density	W_R = 48.		

Normal Operation (+Q, +N)

HAN ($h/α^2$ as a function of υ/α)
HVN ($h/υ^2$ as a function of α/υ)
BAN ($β/α^2$ as a function of υ/α)
BVN ($β/υ^2$ as a function of α/υ)

Energy Dissipation (-Q, +N)

HAD ($h/α^2$ as a function of υ/α)
HVD ($h/υ^2$ as a function of α/υ)
BAD ($β/α^2$ as a function of υ/α)
BVD ($β/υ^2$ as a function of α/υ)

Table B-2 RCP Head & Hydraulic Torque as a Function of Flow and Speed (Fluid Density of 47.892 lbm/ft^3)			
Flow [gpm]	RCP Speed [rpm]	RCP Head [psi]	RCP Hydraulic Torque [ft-lb]
68204.9	1753.	28.274	6398.14
65898.1	1753	37.954	6890.12
65792.4	1753.	38.380	6911.47
51318.8	1753	82.044	8846.70
50511.0	1753.	84.190	8879.96
49432.0	1753.	87.056	8924.37
48300.0	1753.	90.063	8970.89
[redacted]	[redacted]	[redacted]	[redacted]
66473.1	1707.86	26.733	6067.53
[redacted]	[redacted]	[redacted]	[redacted]
49514.6	1692.82	76.616	8251.40
[redacted]	[redacted]	[redacted]	[redacted]
45507.7	1692.0	86.755	8401.66
[redacted]	[redacted]	[redacted]	[redacted]
64817.8	1665.07	25.368	5765.13
[redacted]	[redacted]	[redacted]	[redacted]
47870.5	1636.70	71.627	7713.48
[redacted]	[redacted]	[redacted]	[redacted]
42961.7	1635.0	83.518	7884.01
[redacted]	[redacted]	[redacted]	[redacted]
-5409.8	792.6	35.292	1777.11
[redacted]	[redacted]	[redacted]	[redacted]
-4824.0	792.5	34.781	1760.33
[redacted]	[redacted]	[redacted]	[redacted]
-5594.0	780.28	34.430	1729.67
[redacted]	[redacted]	[redacted]	[redacted]
-5861.9	780.27	34.785	1756.13
[redacted]	[redacted]	[redacted]	[redacted]