NRC 2003-0025

GL 96-06
10 CFR 50.54(f)

March 27, 2003

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

POINT BEACH NUCLEAR PLANT
DOCKETS 50-266 AND 50-301
SUPPLEMENT TO GENERIC LETTER 96-06 RESOLUTION

The NRC staff issued Generic Letter (GL) 96-06 on September 30, 1996. Wisconsin Electric Power Company (WEPCO), then licensee for the Point Beach Nuclear Plant (PBNP), provided its assessment of the waterhammer and two-phase flow issues for PBNP in letters dated January 28, June 25, and December 18, 1997, and related submittals dated September 9, September 30, and October 30, 1996. Responses to NRC requests for additional information were provided on September 4, 1998, and October 12, 2000. With these submittals, the GL 96-06 two-phase flow issues were fully addressed.

Actions to fully address the waterhammer issues were deferred pending completion of the EPRI project and its review and approval by the NRC. EPRI Report TR-113594 was issued in December 2000, and NRC accepted it on April 3, 2002.

On July 30, 2002, Nuclear Management Company, LLC, (NMC) submitted updated information regarding actions to address the resolution of GL 96-06 waterhammer issues at PBNP.

On August 14, 2002, the NRC requested additional information regarding the July 30, 2002, submittal. During a conference call held on August 20, 2002, the NRC staff, PBNP plant staff, and Fauske & Associates (FAI) discussed the additional information requested by the NRC to support their review of Reference 5. During the conference call, PBNP proposed to provide sample cases and additional basis for the rationale that the FAI analyses for PBNP bound the EPRI methodology. On September 10, 2002, NRC staff agreed to review the additional information as proposed by PBNP.

NMC recently replaced all eight containment fan cooler (CFC) units at Point Beach Units 1 and 2. The two-phase flow issues discussed in GL 96-06 were factored into the CFC replacement project. System piping configuration was changed in the course of the system redesign. The analysis provided in the enclosure to this letter is based on the flow and system characteristics of the new CFC unit configurations.

The enclosure to this letter provides the FAI Calculation Note generated to calculate the waterhammer loads for the PBNP Containment Fan Coolers using the EPRI TBR methodology and comparing those results against the results generated previously using TREMOLO. As indicated in the comparison results of the enclosure, FAI concluded that the TREMOLO produced forcing functions used in the PBNP piping stress analyses generally bound the

A072

EPRI TBR forcing functions. NMC agrees with FAI's conclusions. The enclosure demonstrates that the PBNP analyses are conservative with respect to the EPRI methodology.

This letter contains no new commitments and no revision to existing commitments.

A. J. Cayia
Site Vice-President

LAS/kmd

Enclosure:

Transmittal of Fauske & Associates, Inc., Report FAI/03-07, Revision 1: Comparison of Point Beach TREMOLO Calculated Waterhammer Loads with the EPRI TBR Methodology, dated March 10, 2003.

References:

1. NRC Generic Letter (GL) 96-06, Assurance of Equipment Operability and Containment Integrity During Design-Basis Accident Conditions, dated September 30, 1996.
2. Letter from DF Johnson (WE) to Document Control Desk, FL 96-06 120-Day Response, dated January 28, 1997.
3. Letter from AJ Cayia (WE) to Document Control Desk, Revision to GL 96-06, 120-Day Response, dated June 25, 1997.
4. Letter from AJ Cayia (WE) to Document Control Desk, Information pertaining to Implementation of Modifications Associated with GL 96-06, dated December 18, 1997.
5. Letter from B Link (WE) to Document Control Desk, Detailed Operability Evaluation of the Service Water System With Respect to Post-Accident Boiling in Containment Fan Coolers, dated September 9, 1996.
6. Letter from B Link (WE) to Document Control Desk, Evaluation of Steady-State Service Water System Hydraulic Characteristics During A Design Basis Accident, dated September 30, 1996.
7. Letter from B Link (WE) to Document Control Desk, Assurance of Equipment Operability and Containment Integrity During Design Basis Accident Conditions, dated October 30, 1996.
8. Letter from LL Gundrum (NRC) to M. Sellman (WE), Request for Additional Information Regarding Responses to GL 96-06, dated June 25, 1998.
9. Letter from VA Kaminskas (WE) to Document Control Desk, Reply to Request for Additional Information to GL 96-06, dated September 4, 1998.
10. Letter from D Cole (NMC) to Document Control Desk, Reply to Request for Additional Information to GL 96-06, dated October 12, 2000.
11. FAI/97-60 Revision 5, Point Beach Containment Fan Cooler Analysis in Response to Generic Letter 96-06, dated August 8, 2001.

12. EPRI Report TR-113594, Resolution of Generic Letter 96-06 Waterhammer Issues, Volumes 1 and 2, dated December 2000.

13. NRC Acceptance of EPRI Report TR-113594, Resolution of Generic Letter 96-06 Waterhammer Issues, dated April 3, 2002.

14. Letter from D. Spaulding (NRC) to M. Reddemann (NMC), Resolution of Generic Letter 96-06 Waterhammer Issues, dated May 3, 2002.

15. Letter from A. J. Cayia (NMC) to Document Control Desk (NRC), Electric Power Research Institute Report TR-113594, Resolution of Generic Letter 96-06 Waterhammer Issues, dated July 30, 2002.

cc: (w/ enclosure)
Project Manager, Point Beach Nuclear Plant, NRR, USNRC

(w/o enclosure)
Regional Administrator, Region III, USNRC
NRC Resident Inspector - Point Beach Nuclear Plant
PSCW

ENCLOSURE TO NRC 2003-0025

FAUSKE & ASSOCIATES, INC.

TRANSMITTAL OF COMPARISON OF POINT BEACH TREMOLO CALCULATED

WATERHAMMER LOADS WITH THE EPRI TBR METHODOLOGY

POINT BEACH NUCLEAR PLANT, UNITS 1 AND 2

FAUSKE & ASSOCIATES, INC.

CALCULATION NOTE COVER SHEET

SECTION TO BE COMPLETED BY AUTHOR(S):

Calc-Note Number FAI/03-07 Revision Number 1

Title Comparison of Point Beach TREMOLO - Calculated Waterhammer Loads with the EPRI TBR Methodology

Project Point Beach TREMOLO versus EPRI TBR Comparison Project Number or Shop Order WEP015A

Purpose: The purpose of this calculation is to calculate the waterhammer loads for the Point Beach Containment Fan Coolers (CFCs) using the EPRI TBR methodology (EPRI Report #1006456) and comparing these results against the results generated previously using TREMOLO. Revision 1 of this report was issued to address owners acceptance comments. These comments had no bearing on the final conclusions. However, the format of result tables changed slightly.

Results Summary: See Section 5.0 for comparison results of TREMOLO versus the EPRI TBR methodology. It is concluded that the TREMOLO produced forcing functions generally bound the EPRI-TBR forcing functions.

References of Resulting reports, Letters, or Memoranda (Optional)

Author(s): Name (Print or Type)	Signature	Completion Date
R. W. Reeves	R. W. Reeves	3/6/03

SECTION TO BE COMPLETED BY VERIFIER(S):

Verifier(s): Name (Print or Type)	Signature	Completion Date
W. E. Berger	[illegible]	3/6/03

Method of Verification: Design Review ____, Independent Review or Alternate Calculations X, Testing Other (specify)

SECTION TO BE COMPLETED BY MANAGER:

Responsible Manager: Name (Print or Type)	Signature	Approval Date
R. J. Hammersley	R. J. Hammersley	March 10, 2003

CALC NOTE NUMBER FAI/03-07 PAGE 2

CALCULATION NOTE METHODOLOGY CHECKLIST

CHECKLIST TO BE COMPLETED BY AUTHOR(S) (CHECK APPROPRIATE RESPONSE)

1. Is the subject and/or the purpose of the design analysis clearly stated? .... YES ☒ NO ☐

2. Are the required inputs and their sources provided? .... YES ☒ NO ☐ N/A ☐

3. Are the assumptions clearly identified and justified? .... YES ☒ NO ☐ N/A ☐

4. Are the methods and units clearly identified? .... YES ☒ NO ☐ N/A ☐

5. Have the limits of applicability been identified? .... YES ☒ NO ☐ N/A ☐
(Is the analysis for a 3 or 4 loop plant or for a single application.)

6. Are the results of literature searches, if conducted, or other background data provided? .... YES ☐ NO ☐ N/A ☒

7. Are all the pages sequentially numbered and identified by the calculation note number? .... YES ☒ NO ☐

8. Is the project or shop order clearly identified? .... YES ☒ NO ☐

9. Has the required computer calculation information been provided? .... YES ☒ NO ☐ N/A ☐

10 Were the computer codes used under configuration control? .... YES ☒ NO ☐ N/A ☐

11. Was the computer code(s) used applicable for modeling the physical and/or computational problems identified? .... YES ☒ NO ☐ N/A ☐
(i.e., Is the correct computer code being used for the intended purpose.)

12. Are the results and conclusions clearly stated? .... YES ☒ NO ☐

13 Are Open Items properly identified .... YES ☐ NO ☐ N/A ☒

14. Were approved Design Control practices followed without exception? .... YES ☒ NO ☐ N/A ☐
(Approved Design Control practices refers to guidance documents within Nuclear Services that state how the work is to be performed, such as how to perform a LOCA analysis.)

15. Have all related contract requirements been met? .... YES ☒ NO ☐ N/A ☐

NOTE:

If NO to any of the above, Page Number containing justification ____________

FAI/03-07

COMPARISON OF POINT BEACH TREMOLO-CALCULATED WATERHAMMER LOADS WITH THE EPRI TBR METHODOLOGY

Rev. 1

Prepared for

Nuclear Management Co. LLC

Prepared by

Fauske & Associates, Inc.
16W070 West 83rd St.
Burr Ridge, IL 60521

March 2003

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1.0 PURPOSE

The purpose of this calculation is to calculate the waterhammer loads for the Point Beach Containment Fan Coolers (CFCs) using the EPRI Waterhammer Issues TBR (EPRI, 2002a) Methodology. These calculations will be performed on an elevated fan cooler and a lower fan cooler (in terms of elevation within containment) for Point Beach Units 1 and 2. The results of these calculations will then be compared against the results generated for the previously performed TREMOLO analyses (FAI, 2000 and 2001a & b). This comparison is being performed to satisfy NRC requirements for Generic Letter 96-06 as discussed in Section 2.0

2.0 INTRODUCTION

In response to the requirements of NRC Generic Letter 96-06 (NRC, 1996), the waterhammer loads associated with column separation and energy transfer to the service water system (including the containment fan coolers) were analyzed using the FAI computer code TREMOLO Revision 1.02 (FAI, 1997). The analyses were performed for all of the fan cooler piping arrangements in both units and were based on the design basis accident conditions of a loss of off-site power event (LOOP), as well as a loss of off-site power combined with a large break loss of coolant accident (LOCA) in the containment (LOOP + LOCA).

These conditions were evaluated with the TREMOLO code and the resulting waterhammer loads associated with both condensation induced waterhammer and column closure following separation were assessed for the entire length of the fan cooler piping. These time dependent loads were transmitted to Sargent & Lundy to be analyzed with respect to the piping response to determine the associated loads on the piping hangers. The net result of this integrated analysis was that all of the piping hangers remained within their design basis loadings for both of the service water transients investigated. In general, the LOOP + LOCA transient provided the greatest loads.

Since the TREMOLO code has not been generically reviewed by the Nuclear Regulatory Commission (NRC), closure of the issues identified in NRC Generic Letter 96-06 (NRC, 1996) requires either a review of the computer code by the NRC or a comparison between the results generated for the Point Beach units and a generic methodology which has been approved by the NRC. Generic approval has been given to the EPRI methodology Generic Letter 96-06 Waterhammer Issues Resolution Technical Basis Report (EPRI, 2002a) for evaluating loads resulting from column closure events which is intended to bound condensation induced waterhammer events. This calculation compares the calculated loads using the EPRI TBR methodology with those produced using the TREMOLO code.

3.0 REFERENCES

EPRI, 2002a, "Generic Letter 96-06 Waterhammer Issues Resolution - Technical Basis Report - Non Proprietary," EPRI Report # 1003097, May 2002.

EPRI, 2002b, "Generic Letter 96-06 Waterhammer Issues Resolution - User's Manual," EPRI Report # 1006456, April, 2002.

Fauske & Associates, Inc. 1997, FAI Q.A. File 5.17 (includes TREMOLO Revision 1 Test Plan, Test Documentation, and User Documentation, March 1997 and TREMOLO Revision 1.02 Software Change Specification and Test Documentation, August 1997).

Fauske & Associates, Inc., 2000, "Point Beach Containment Fan Cooler Analysis in Response to NRC Generic Letter 96-06," FAI/97-60, Rev. 2.

Fauske & Associates, Inc., 2001a, "Point Beach Containment Fan Cooler Analysis in Response to NRC Generic Letter 96-06," FAI/97-60, Rev. 3.

Fauske & Associates, Inc. 2001b, "Point Beach Containment Fan Cooler Analysis in Response to NRC Generic Letter 96-06," FAI/97-60, Rev. 5.

NRC, 1996, "Generic Letter 96-06: Assurance of Equipment Operability and Containment Integrity During Design Basis Accident Conditions," September 30, 1996.

WEPCo, 1999, Point Beach FSAR: Section 9.6 (Service Water System), Rev. 6. 1999.

WEPCo, 2003, E-mails from Chuck Richardson (WEPCo) to R. J. Hammersley (FAI) dated 1/27/03 and 1/28/03, "Unit 1 & 2 WATER model output."

4.0 DESIGN INPUTS

The objective of this calculation is to compare the loads calculated by TREMOLO and EPRI TBR due to column closure waterhammer once steam bubbles have been generated due to energy addition and a pressure reduction. The TREMOLO loads for each of eight fan coolers at Point Beach have been previously calculated and the results are documented in (FAI, 2000, 2001a, 2001b). Tables 4-1 through 4-4 illustrate the design inputs required for the EPRI TBR methodology and the actual values used for the analyses performed on Point Beach CFCs 1A, 1C, 2B and 2D. Figure 4-1 illustrates a graphic representation of the EPRI TBR CFC model used to perform the pressure pulse calculations.

As shown in Figure 4-1, the EPRI TBR methodology does not model the 6" and 2 ½" piping that branch off the 8"piping on the supply and return side of the CFC. This is due to the fact that the EPRI methodology does not model parallel flow paths, which is what occurs immediately before and after flow enters and exits the CFCs. However, since TREMOLO demonstrated that the peak forces occur in the 8" piping and the void collapse occurs in this piping as well, the 6" and 2 ½" piping does not need to be modeled. The forces in the 6" and 2 ½" piping could be calculated using transmission coefficients calculated in the EPRI TBR methodology. Based on such transmission coefficients, the pressure pulses produced by void collapse in the 8" piping are reduced as they are transmitted to 6" piping and even further reduced when the pressure is then transmitted into the 2 ½" piping. Therefore, due to these pressure reductions the 6" and 2 ½" piping do not need to be modeled directly.

The approach for developing the comparison was completed as follows:

- Select two fan cooler units per unit based on elevational differences within containment (high and low elevation).
- Assemble the information for the EPRI TBR calculation based on the piping configuration documented in the various TREMOLO parameter files for the selected CFCs for analysis.

- Calculate the peak pressure pulse using the EPRI TBR methodology. The MathCad 2000 spreadsheet used to calculate the peak pressure pulses for the four Point Beach CFCs was developed and tested by implementing the EPRI Open Loop Example Problem (EPRI, 2002b) and verifying that identical results were produced.
- Apply the EPRI TBR calculated pressure pulse using the methodology described in Figure 5-5 to determine the loads (peak force/impulse) from the TBR evaluations for the selected CFCs.
- Determine the maximum forces from the previous TREMOLO analyses [FAI, 2000, 2001a, 2001b] and calculate the impulses associated with those forces.
- Compare the results generated from the TREMOLO analyses to the results generated from the EPRI TBR methodology.

4.1 Assumptions

Several assumptions were made in the EPRI TBR calculations for the Point Beach CFCs. Listed below is a summary of the assumptions made in this analysis:

- The SW design temperature is used to calculate the amount of non-condensable gases that comes out of solution in the EPRI Waterhammer Calculations. A conservatively high temperature of 95°F was assumed. This is conservative since a higher water temperature results in smaller amounts of non-condensable gases, which leads to less "cushioning" during void collapse.
- Figure 4-1 illustrates two "other system loads" in the EPRI CFC model. The upper branch (b to f) "other system loads" (Q_{abf}) was assumed to be the second fan cooler that branches off the supply header. Its flow was assumed to be ≈ 800 gpm. The lower branch (a to g) "other system load" (Q_{ag}) in the 24" line was assumed to be equal to the total flow out of a SW pump minus the two CFC flows.

Table 4-1: EPRI TBR Calculational Inputs for Point Beach CFC 1A		
TBR Parameter	**Value**	**Description/Reference**
T_{void}	224 F	Average void temperature when pumps restart [FAI, 2001a]
P_{void}	18.3 psia	Saturation pressure of T_{void} (steam table)
T_{pipe}	75 F	Initial pipe temperature [FAI, 2001a] (not used in EPRI methodology)
P_{atm}	14.7 psia	Atmospheric pressure (absolute)
N_{tube}	240	Number of fan cooler tubes [FAI, 2001a]
ID_{tube}	0.527"	ID of fan cooler tubes [FAI, 2001a]
L_{tube}	22 ft	Length of fan cooler tubes [FAI, 2001a]
EL_1	33.2 ft	Elevation of node 1 [FAI, 2001a]
EL_2*	82.3 ft	Elevation of node 2 [FAI, 2001a]
L_{ab}	30.5 ft	Length from node A to B [FAI, 2001a]
L_{bc}	87.5 ft	Length from node B to C [FAI, 2001a]
L_{cd}	61.4 ft	Length from node C to D [FAI, 2001a]
L_{de}	78.5 ft	Length from node D to E [FAI, 2001a]
L_{ef}	4.1 ft	Length from node E to F [FAI, 2001a]
L_{fg}	87.6 ft	Length from node F to G [FAI, 2001a]
ID_{abf}	13.124 in	ID of piping along path a→b→f [FAI, 2001a]
ID_{bcd}	7.981 in	ID of piping along path b→c→d [FAI, 2001a]
ID_{ag}	22.624 in	ID of piping along path a→g [FAI, 2001a]
OD_{bcd}	8.625 in	OD of piping along path b→c→d FAI, 2001a]
H_s	240.8 ft	Pump shutoff head [WEPCo, 2003] (See Appendix E)
A_1	0.2547 sec/ft^2	1st order pump curve coefficient [WEPCo, 2003] (See Appendix E)
A_2	-0.5783 sec^2/ft^5	2nd order pump curve coefficient [WEPCo, 2003] (See Appendix E)
Q_{abf}	800 gpm	Flow along path a→b→f during steady state (assumed)
Q_{bcd}	917 gpm	Flow along path b→c→d during steady state [FAI, 2001a]
Q_{ag}	5100 gpm	Flow along path a→g during steady state [WEPCo, 1999]
$V_{wtr\text{-}fcu}$	0.0 ft^3	Volume of water present in FCU when pump restarts [FAI, 2001a]
K_{valve}	158.41	Throttle valve loss coefficient [FAI, 2001a]
ρ_{wtr}	62 lb/ft^3	Water density
T_{des}	95 F	Design temp of Service Water System (assumed)
R_{gas}	1717 ft^2/sec$^2 \cdot$ R	Universal gas constant
P_{sys}	19 psig	Initial steady state system pressure [FAI, 2001a]

Note: *Since the Point Beach CFCs have check valves on the 8" supply piping to the CFC, the void elevation (EL_2) illustrated in Figure 4-1 will not be the same on the supply and return side of the CFC piping. For these analyses, EL_2 was calculated to be the elevation of the void front on the supply side of the CFC. This is appropriate since EL_2 is only used to determine the water head the SW pump must overcome.

Table 4-2: EPRI TBR Calculational Inputs for Point Beach CFC 1C		
TBR Parameter	**Value**	**Description/Reference**
T_{void}	223.0 F	Average void temperature when pumps restart [FAI, 2001b]
P_{void}	18.3 psia	Saturation pressure of T_{void} (steam table)
T_{pipe}	75 F	Initial pipe temperature [FAI, 2001b] (not used in EPRI methodology)
P_{atm}	14.7 psia	Atmospheric pressure (absolute)
N_{tube}	240	Number of fan cooler tubes [FAI, 2001b]
ID_{tube}	0.527"	ID of fan cooler tubes [FAI, 2001b]
L_{tube}	22 ft	Length of fan cooler tubes [FAI, 2001b]
EL_1	33.2 ft	Elevation of node 1 [FAI, 2001b]
EL_2*	37.4 ft	Elevation of node 2 [FAI, 2001b]
L_{ab}	30.5 ft	Length from node A to B [FAI, 2001b]
L_{bc}	67.8 ft	Length from node B to C [FAI, 2001b]
L_{cd}	32.3ft	Length from node C to D [FAI, 2001b]
L_{de}	79.8 ft	Length from node D to E [FAI, 2001b]
L_{ef}	2.2 ft	Length from node E to F [FAI, 2001b]
L_{fg}	86.4 ft	Length from node F to G [FAI, 2001b]
ID_{abf}	13.124 in	ID of piping along path a→b→f [FAI, 2001b]
ID_{bcd}	7.981 in	ID of piping along path b→c→d [FAI, 2001b]
ID_{ag}	22.624 in	ID of piping along path a→g [FAI, 2001b]
OD_{bcd}	8.625 in	OD of piping along path b→c→d FAI, 2001b]
H_s	240.8 ft	Pump shutoff head [WEPCo, 2003] (See Appendix E)
A_1	0.2547 sec/ft^2	1st order pump curve coefficient [WEPCo, 2003] (See Appendix E)
A_2	-0.5783 sec^2/ft^5	2nd order pump curve coefficient [WEPCo, 2003] (See Appendix E)
Q_{abf}	800 gpm	Flow along path a→b→f during steady state (assumed)
Q_{bcd}	851 gpm	Flow along path b→c→d during steady state [FAI, 2001b]
Q_{ag}	5200 gpm	Flow along path a→g during steady state [WEPCo, 1999]
$V_{wtr-fcu}$	0.0 ft^3	Volume of water present in FCU when pump restarts [FAI, 2001b]
K_{valve}	161.472	Throttle valve loss coefficient [FAI, 2001b]
ρ_{wtr}	62 lb/ft^3	Water density
T_{des}	95 F	Design temp of Service Water System (assumed)
R_{gas}	1717 ft^2/sec^2 · R	Universal gas constant
P_{sys}	19 psig	Initial steady state system pressure [FAI, 2001b]

Note: *Since the Point Beach CFCs have check valves on the 8" supply piping to the CFC, the void elevation (EL_2) illustrated in Figure 4-1 will not be the same on the supply and return side of the CFC piping. For these analyses, EL_2 was calculated to be the elevation of the void front on the supply side of the CFC. This is appropriate since EL_2 is only used to determine the water head the SW pump must overcome.

Table 4-3: EPRI TBR Calculational Inputs for Point Beach CFC 2B		
TBR Parameter	**Value**	**Description/Reference**
T_{void}	217.1 F	Average void temperature when pumps restart [FAI, 2000]
P_{void}	16.3 psia	Saturation pressure of T_{void} (steam table)
T_{pipe}	75 F	Initial pipe temperature [FAI, 2000] (not used in EPRI methodology)
P_{atm}	14.7 psia	Atmospheric pressure (absolute)
N_{tube}	240	Number of fan cooler tubes [FAI, 2000]
ID_{tube}	0.527"	ID of fan cooler tubes [FAI, 2000]
L_{tube}	22 ft	Length of fan cooler tubes [FAI, 2000]
EL_1	33.2 ft	Elevation of node 1 [FAI, 2000]
EL_2*	72.0 ft	Elevation of node 2 [FAI, 2000]
L_{ab}	36.8 ft	Length from node A to B [FAI, 2000]
L_{bc}	139.4 ft	Length from node B to C [FAI, 2000]
L_{cd}	83.6 ft	Length from node C to D [FAI, 2000]
L_{de}	129.2 ft	Length from node D to E [FAI, 2000]
L_{ef}	4.8 ft	Length from node E to F [FAI, 2000]
L_{fg}	118.6 ft	Length from node F to G [FAI, 2000]
ID_{abf}	13.124 in	ID of piping along path a→b→f [FAI, 2000]
ID_{bcd}	7.981 in	ID of piping along path b→c→d [FAI, 2000]
ID_{ag}	22.624 in	ID of piping along path a→g [FAI, 2000]
OD_{bcd}	8.625 in	OD of piping along path b→c→d FAI, 2000]
H_s	240.8 ft	Pump shutoff head [WEPCo, 2003] (See Appendix E)
A_1	0.2547 sec/ft^2	1st order pump curve coefficient [WEPCo, 2003] (See Appendix E)
A_2	-0.5783 sec^2/ft^5	2nd order pump curve coefficient [WEPCo, 2003] (See Appendix E)
Q_{abf}	800 gpm	Flow along path a→b→f during steady state (assumed)
Q_{bcd}	886 gpm	Flow along path b→c→d during steady state [FAI, 2000]
Q_{ag}	5200 gpm	Flow along path a→g during steady state [WEPCo, 1999]
$V_{wtr\text{-}fcu}$	0.0 ft^3	Volume of water present in FCU when pump restarts [FAI, 2000]
K_{valve}	165.447	Throttle valve loss coefficient [FAI, 2000]
ρ_{wtr}	62 lb/ft^3	Water density
T_{des}	95 F	Design temp of Service Water System (assumed)
R_{gas}	1717 $ft^2/sec^2 \cdot R$	Universal gas constant
P_{sys}	19 psig	Initial steady state system pressure [FAI, 2000]

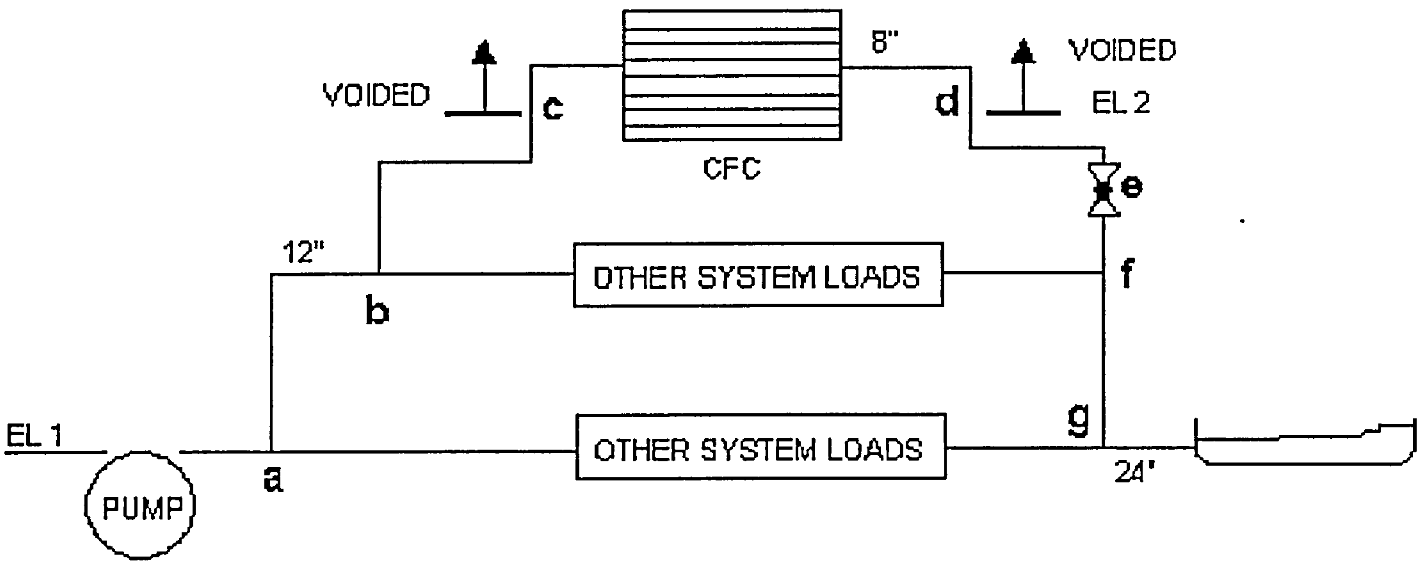
Note: *Since the Point Beach CFCs have check valves on the 8" supply piping to the CFC, the void elevation (EL_2) illustrated in Figure 4-1 will not be the same on the supply and return side of the CFC piping. For these analyses, EL_2 was calculated to be the elevation of the void front on the supply side of the CFC. This is appropriate since EL_2 is only used to determine the water head the SW pump must overcome.

Table 4-4: EPRI TBR Calculational Inputs for Point Beach CFC 2D

TBR Parameter	Value	Description/Reference
T_{void}	204.4 F	Average void temperature when pumps restart [FAI, 2000]
P_{void}	12.7 psia	Saturation pressure of T_{void} (steam table)
T_{pipe}	75 F	Initial pipe temperature [FAI, 2000] (not used in EPRI methodology)
P_{atm}	14.7 psia	Atmospheric pressure (absolute)
N_{tube}	240	Number of fan cooler tubes [FAI, 2000]
ID_{tube}	0.527"	ID of fan cooler tubes [FAI, 2000]
L_{tube}	22 ft	Length of fan cooler tubes [FAI, 2000]
EL_1	33.2 ft	Elevation of node 1 [FAI, 2000]
EL_2*	30.3 ft	Elevation of node 2 [FAI, 2000]
L_{ab}	36.8 ft	Length from node A to B [FAI, 2000]
L_{bc}	161.8ft	Length from node B to C [FAI, 2000]
L_{cd}	46.5 ft	Length from node C to D [FAI, 2000]
L_{de}	161.2 ft	Length from node D to E [FAI, 2000]
L_{ef}	6.4 ft	Length from node E to F [FAI, 2000]
L_{fg}	86.8 ft	Length from node F to G [FAI, 2000]
ID_{abf}	13.124 in	ID of piping along path a→b→f [FAI, 2000]
ID_{bcd}	7.981 in	ID of piping along path b→c→d [FAI, 2000]
ID_{ag}	22.624 in	ID of piping along path a→g [FAI, 2000]
OD_{bcd}	8.625 in	OD of piping along path b→c→d FAI, 2000]
H_s	240.8 ft	Pump shutoff head [WEPCo, 2003] (See Appendix E)
A_1	0.2547 sec/ft^2	1st order pump curve coefficient [WEPCo, 2003] (See Appendix E)
A_2	-0.5783 sec^2/ft^5	2nd order pump curve coefficient [WEPCo, 2003] (See Appendix E)
Q_{abf}	800 gpm	Flow along path a→b→f during steady state (assumed)
Q_{bcd}	949 gpm	Flow along path b→c→d during steady state [FAI, 2000]
Q_{ag}	5100 gpm	Flow along path a→g during steady state [WEPCo, 1999]
$V_{wtr\text{-}fcu}$	0.0 ft^3	Volume of water present in FCU when pump restarts [FAI, 2000]
K_{valve}	139.326	Throttle valve loss coefficient [FAI, 2000]
ρ_{wtr}	62 lb/ft^3	Water density
T_{des}	95 F	Design temp of Service Water System (assumed)
R_{gas}	1717 ft^2/sec^2 · R	Universal gas constant
P_{sys}	19 psig	Initial steady state system pressure [FAI, 2000]

Note: *Since the Point Beach CFCs have check valves on the 8" supply piping to the CFC, the void elevation (EL_2) illustrated in Figure 4-1 will not be the same on the supply and return side of the CFC piping. For these analyses, EL_2 was calculated to be the elevation of the void front on the supply side of the CFC. This is appropriate since EL_2 is only used to determine the water head the SW pump must overcome.

Figure 4-1 Diagram of EPRI TBR CFC Configuration (Open System).



5.0 RESULTS

5.1 EPRI TBR Waterhammer Calculations

During a postulated LOCA (or MSLB) with a concurrent LOOP (Loss of Offsite Power), the service water pumps that supply cooling water to the CFCs and the fans that supply air to the CFCs will temporarily lose power. The cooling water will lose pressure and stop faster than the fans stop. During the fan coastdown, the high temperature steam in the containment atmosphere will pass over the CFC tubing with no forced cooling water flowing through the tubing. Boiling may occur in the CFC tubing causing steam bubbles to form in the CFCs and pass into the attached piping creating steam voids. Prior to pump restart, the presence of steam and subcooled water presents the potential for waterhammer. As the service water pumps restart, the accumulated steam will condense and the pumped water can produce a waterhammer when the void collapses. The hydrodynamic loads introduced to the service water piping by such a waterhammer event could challenge the integrity and function of the CFCs and the Service Water (SW) System, as well as containment integrity, should the waterhammer loads fail the Service Water piping supports.

Section 7.0 of the EPRI TBR Waterhammer Users Manual (EPRI, 2002b) provides a prescribed methodology to calculate the pressure pulse due to a SW system column closure waterhammer event. The analysis is performed in the following manner:

- Calculate the initial closing velocity
- Calculate the lengths of the accelerating water column
- Calculate the mass of gas in the voided region
- Calculate a "cushioned" velocity based on initial velocity, pipe size, void and column length
- Calculate sonic velocity
- Calculate the waterhammer pressure pulse rise time
- Calculate the pulse duration
- Calculate the transmission coefficients

- Calculate the pulse pressure with no clipping
- Calculate the pressure considering clipping
- Calculate the pressure pulse shape.

Using this methodology and the design information specified in Tables 4-1 through 4-4, the calculations for the Point Beach CFCs using the EPRI TBR methodology were performed and the calculation for each of the four Point Beach CFCs (1HX15A, 1HX15C, 2HX15B, and 2HX15D) is attached as Appendices A through D. Table 5-1 summarizes the results and Figures 5-1 through 5-4 illustrate the EPRI TBR calculated pressure pulses for each of the four Point Beach CFCs.

The pressure pulse calculated (see Figures 5-1 through 5-4) for each of the four Point Beach CFCs were then used to calculate the force history and impulse loading on the SW piping upstream and downstream for each of the four CFCs analyzed. The void collapse location was determined from the corresponding TREMOLO results [FAI, 2000, 2001a, and 2001b]. Figure 5-5 illustrates the manner in which the forces/impulse will be calculated when applying the EPRI-calculated pressure pulse to the Point Beach SW piping. Since the void collapse occurs in the return line, the force and impulse calculations focused on the piping between the CFC outlet header which is upstream of the void collapse and the MOV throttling valve that is downstream of the void collapse.

As shown in Figure 5-5, the EPRI-calculated pressure pulse (b) can be applied to a pipe network (a) to calculate the force on the two elements P_1 and P_2 (c). The force on P_1 is simply equal to the pressure times the pipe area. Since the pipe diameter is the same at points P_1 and P_2, the force magnitude on P_2 is the same as P_1, except it is in the opposite direction and delayed by the transient pressure pulse's transient time between the two points. The transient time equals the length of the pipe between P_1 and P_2 (L_2) divided by the sonic velocity. Due to the delay in the pressure pulse reaching P_2, the pipe section experiences an unbalanced force until the pressure pulse reaches P_2. Therefore, due to this time delay and the forces being in the opposite direction, the resulting force (d) on the pipe section between P_1 and P_2 is used to determine the peak forces and impulses.

Table 5-1 Results of EPRI TBR Waterhammer Calculations for Point Beach CFCs

	Unit 1		Unit 2	
	CFC 1A	CFC 1C	CFC 2B	CFC 2D
Rise time (ms)	48	39	39	28
Duration (ms)	79.7	78.8	118.2	119.1
ΔP (psi)	191	202	223	286
$\Delta P_{no\ clipping}$	174	222	203	260
Refill velocity ($V_{initial}$) ft/s	7.9	8.8	8.5	10.9
Cushion velocity ($V_{cushion}$) ft/s	6.1	7.1	7.1	9.1
Total duration (ms)*	127	118	157	147

Figure 5-1 EPRI TBR Waterhammer Pressure Pulse for Point Beach CFC 1A.

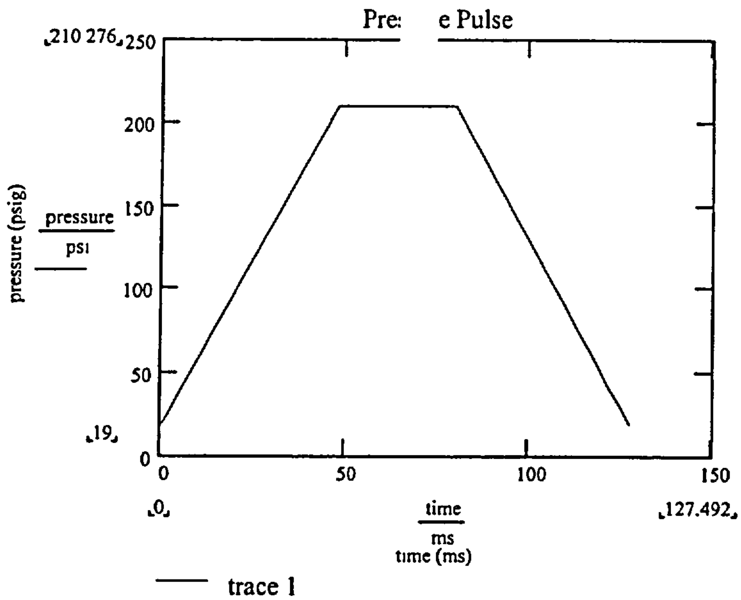


Figure 5-2 EPRI TBR Waterhammer Pressure Pulse for Point Beach CFC 1C.

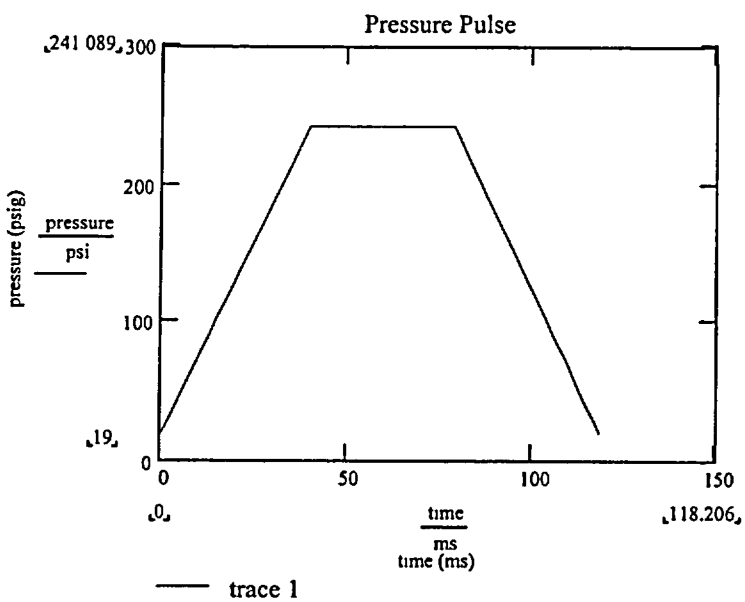


Figure 5-3 EPRI TBR Waterhammer Pressure Pulse for Point Beach CFC 2B.

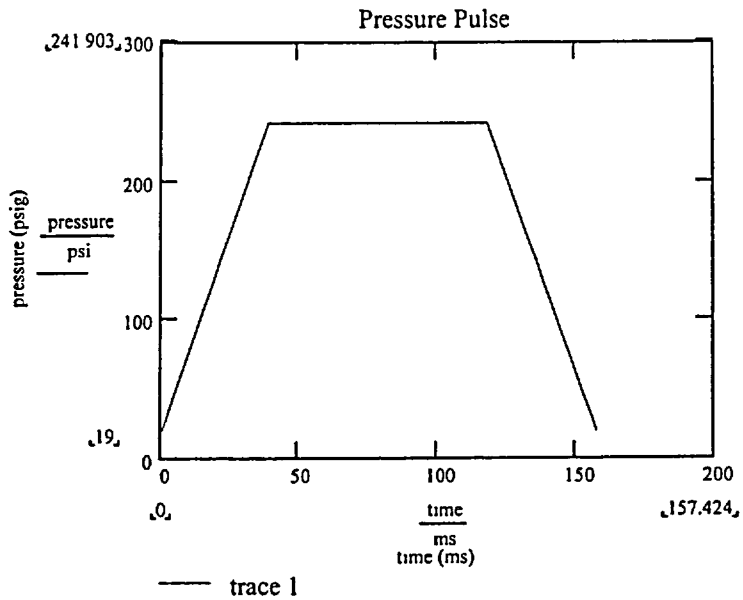


Figure 5-4 EPRI TBR Waterhammer Pressure Pulse for Point Beach CFC 2D.

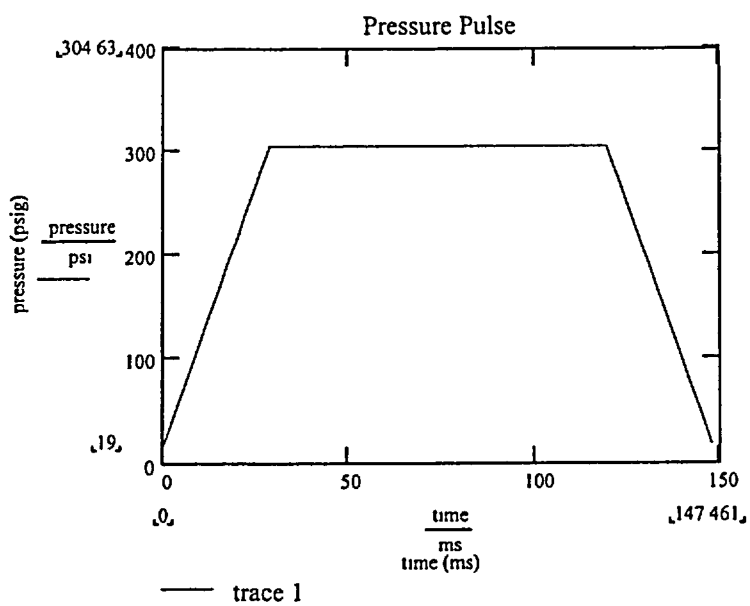
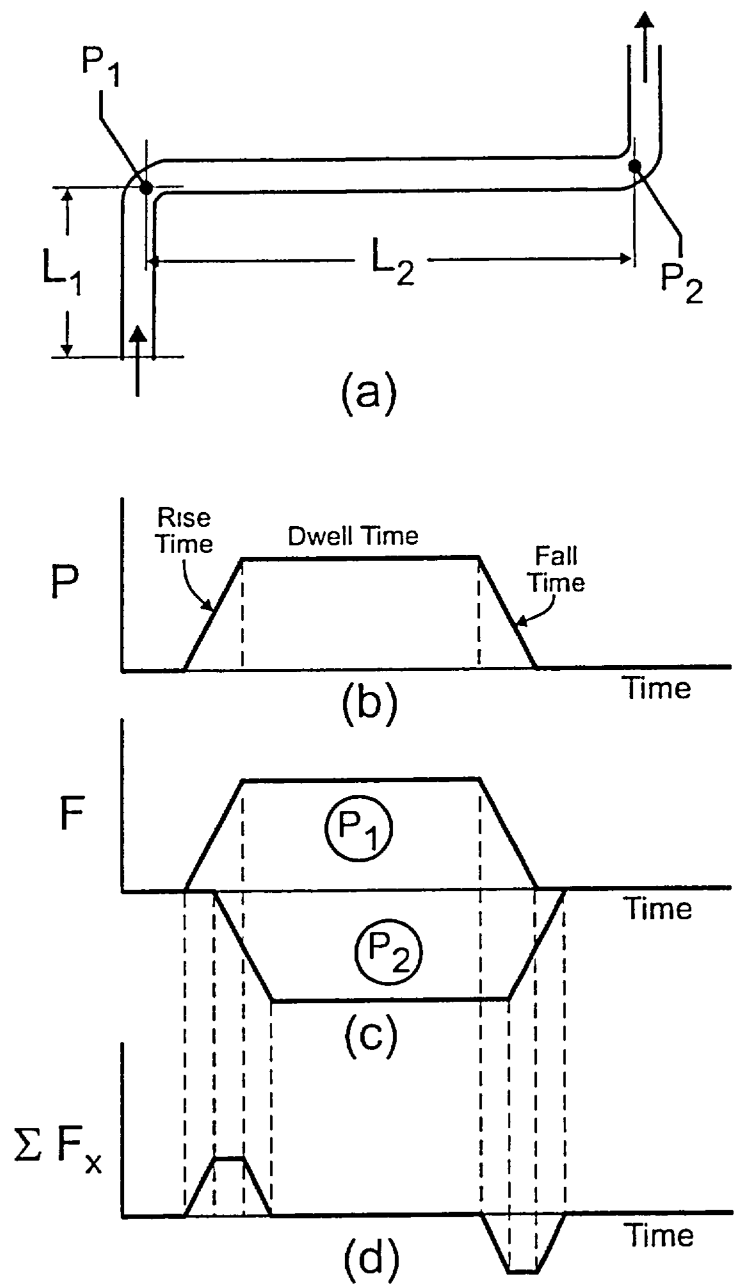


Figure 5-5 EPRI Pressure-Force Time History Schematic.



RR032001 CDR 2-28-2003

The resulting force (d) begins to rise once the pressure pulse reaches P_1 and continues to rise until the pressure pulse reaches P_2. When the pressure pulse reaches P_2, the resulting force levels out until the pressure pulse at P_1 reaches its peak at which time the resultant force turns around and goes to zero when the pressure pulse at P_2 reaches its peak. The force in the pipe remains balanced until the pressure pulse begins to exit P_1. The resulting force then goes in the negative direction until the pressure pulse begins to exit P_2. At this time the forces balance until the pressure pulse completely exits P_1. The resultant force then goes to zero as the pressure pulse completely clears P_2.

The maximum forces and impulses are tabulated in Tables 5-2b through 5-5b for the four Point Beach CFCs. The maximum force and impulses were calculated assuming a single pressure pulse calculated for each CFC (shown in Appendices A through D) is propagated through the SW piping. The point of collapse for the calculation was assumed to be at the same location of final void collapse calculated by TREMOLO for each CFC. The peak forces and impulse calculation for each of the fan CFCs analyzed are attached as Appendices F through I. As shown in these Appendices and Figure 5-5, the peak force is limited by the length of piping between two sequential elements (i.e., elbow). Once the pressure pulse reaches one elbow it begins to exert a force on the section of piping between the two elements. However, when the pressure pulse is transmitted to the next elbow, which is length of pipe divided by the sonic velocity of the pulse, the force on the second element counteracts the first force, thus limiting the peak force on the piping due to the relatively short length of piping between the various elements within the system (typically less then 20 ft). The pipe section peak forces and corresponding impulses (calculated as the rise time of the pressure pulse x the peak resultant force) are summarized in Tables 5-2b through 5-5b for each of the four CFCs analyzed.

5.2 TREMOLO Peak Force/Impulse Calculations

The TREMOLO peak forces were taken from the previously performed TREMOLO analyses [FAI, 2000, 2001a and 2001b] on the Point Beach CFCs. The corresponding impulse for these forces was not directly calculated in the TREMOLO analyses referenced above, rather they were determined separately by conservatively estimating the area under the peak force pulses.

Table 5-2a Comparison of TREMOLO - EPRI TBR Maximum Forces for Point Beach CFC 1A.

TREMOLO-Calculated Maximum Force (lb_f)	EPRI-Calculated Maximum Force (lb_f)
1858	907
1840	605
1796	592
1702	559
1633	488
1201	326
997	302

Table 5-2b Comparison of TREMOLO - EPRI TBR Maximum Impulses for Point Beach CFC 1A.

TREMOLO-Calculated Impulses ($lb_f \cdot s$)	EPRI-Calculated Impulses ($lb_f \cdot s$)
103.3	43.5
65.6	29.1
65.0	28.4
64.8	26.8
41.4	23.4
36.6	15.6
36.0	14.5

Table 5-3a Comparison of TREMOLO - EPRI TBR Maximum Forces for Point Beach CFC 1C.

TREMOLO-Calculated Maximum Force (lb_f)	EPRI-Calculated Maximum Force (lb_f)
3119	1200
2917	732
2545	732
2422	732
1950	706
1599	580
1303	535

Table 5-3b Comparison of TREMOLO - EPRI TBR Maximum Impulses for Point Beach CFC 1C.

TREMOLO-Calculated Impulses ($lb_f \cdot s$)	EPRI-Calculated Impulses ($lb_f \cdot s$)
102.5	46.8
68.9	28.6
63.3	28.6
62.5	28.6
58.5	27.5
35.5	22.6
32.1	20.9

Table 5-4a Comparison of TREMOLO - EPRI TBR Maximum Forces for Point Beach CFC 2B.

TREMOLO-Calculated Maximum Forces (lb_f)	EPRI-Calculated Maximum Forces (lb_f)
2619	2408
1664	1299
1248	1144
1039	943
898	870
889	678
822	613

Table 5-4b Comparison of TREMOLO - EPRI TBR Maximum Impulses for Point Beach CFC 2B.

TREMOLO-Calculated Impulses ($lb_f \cdot s$)	EPRI-Calculated Impulses ($lb_f \cdot s$)
104.3	93.9
75.0	50.6
65.3	44.6
63.9	36.8
49.9	33.9
40.6	26.4
37.5	23.9

Table 5-5a Comparison of TREMOLO - EPRI TBR Maximum Forces for Point Beach CFC 2D.

TREMOLO-Calculated Maximum Forces (lb_f)	EPRI-Calculated Maximum Forces (lb_f)
3551	4779
3264	3596
2670	1541
1521	1075
1516	1075
1474	836
1330	818

Table 5-5b Comparison of TREMOLO - EPRI TBR Maximum Impulses for Point Beach CFC 2D.

TREMOLO-Calculated Impulses (lb_f)	EPRI-Calculated Impulses ($lb_f \cdot s$)
283.5	133.8
254.8	100.7
166.9	43.2
90.2	30.1
88.5	30.1
73.4	23.4
63.5	22.9

The peak forces and impulses tabulated in Tables 5-2a through 5-5a for the four Point Beach CFCs analyzed were identified and tabulated independently.

As stated earlier in Section 2.0, TREMOLO is a transient code that models the fluid hydrodynamics within the SW piping system as well as performs pressure and force calculations in the piping network following a waterhammer event. TREMOLO also considers distributed voids in several pipe segments which upon collapse will transmit a pressure pulse. A sample illustration of these multiple pressure pulses is illustrated in Figure 5-6. As shown in Figure 5-6, the pressure response through this particular piping event is very dynamic. This is due to the fact that once TREMOLO calculates void collapse within a node, a pressure pulse is calculated and is transmitted throughout the system. In addition, TREMOLO models the pressure wave transmission and reflections. The net result is numerous pressure waves traveling through the SW system as the voids collapse throughout the piping system. Since the void collapse occurs in the CFC return line, the TREMOLO force and impulse calculations focused on the piping between the CFC outlet header which is upstream of the void collapse and the MOV throttling valve which is downstream of the void collapse.

The pressure pulses traveling throughout the system exert forces on the piping as shown in Figure 5-7. Figure 5-7 illustrates the force history for a typical pipe segment during the time interval when the pumps would restart and voids would begin to collapse. As shown in this figure, TREMOLO predicts that a pipe segment will undergo numerous force pulses throughout this time window. However, since TREMOLO calculates the multiple force pulses as a function of time and the EPRI TBR methodology yields a single pulse through the SW piping, the values listed in Tables 5-2a through 5-5a only consider the single maximum force pulse calculated by TREMOLO over a pipe element and its corresponding impulse. As shown in Figure 5-7, the SW piping forces are very dynamic and the piping forces are "pushing and pulling" the piping and pipe restraints for each period of time (i.e., tens of seconds) such that the TREMOLO analyses performed on the Point Beach CFCs provided a dynamic force-time history analysis.

Figure 5-6 Sample TREMOLO Pressure Profile for a Point Beach SW Piping Element Following a LOOP + LOCA.

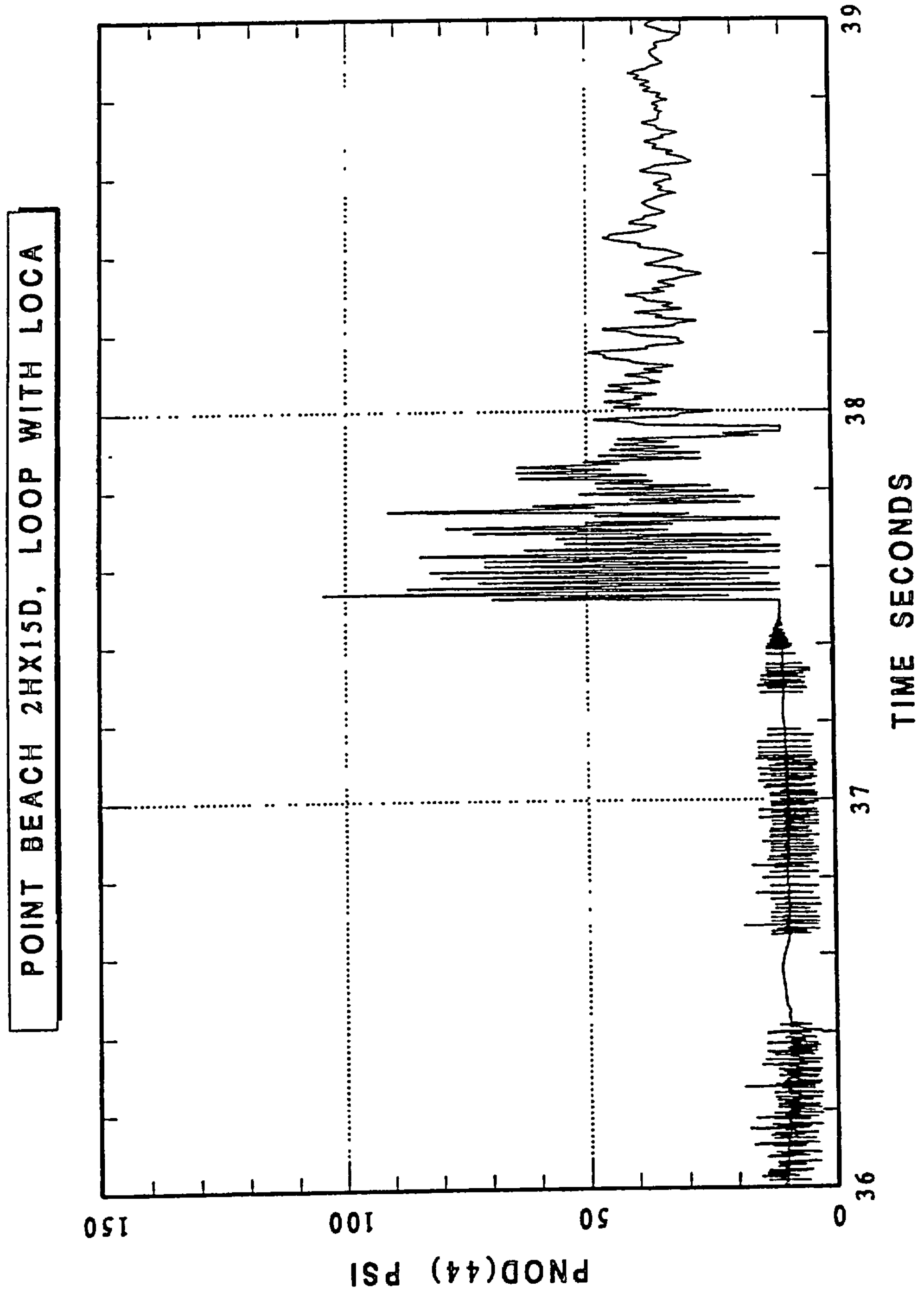
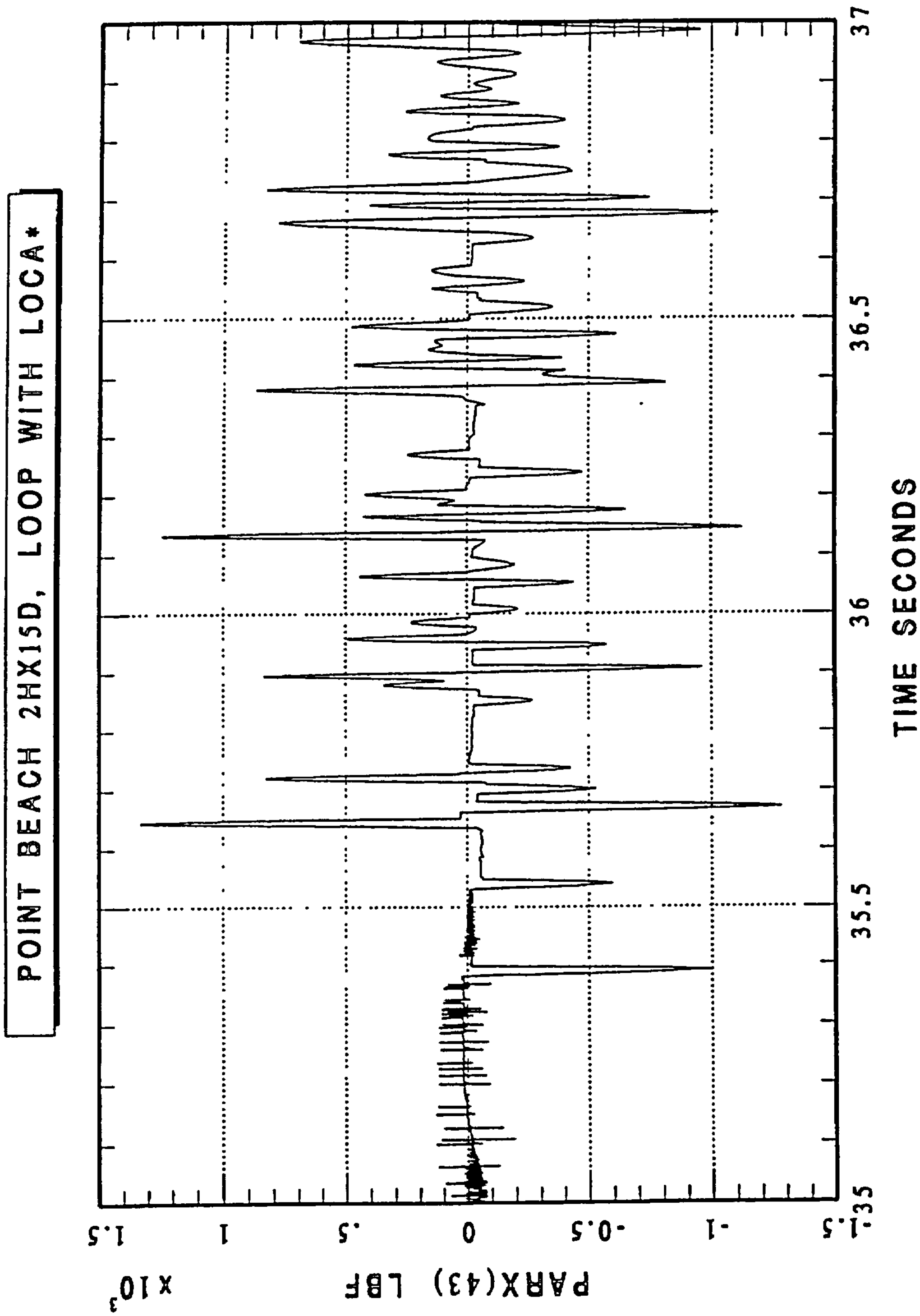


Figure 5-7 Sample TREMOLO Force Time History for a Point Beach SW Piping Element Following a LOOP + LOCA.



6.0 CONCLUSIONS

The results of the comparison of the EPRI TBR methodology versus the TREMOLO code for calculating the peak forces and impulse loading on the SW piping due to waterhammer events following a LOOP + LOCA event are summarized in Tables 5-2 through 5-5. The impulses were included in this comparison because they provide a measure of the dynamic character of the forcing function when comparing the overall loads that pipe supports/restraints must overcome when pressure induced loads are calculated to occur within the piping. The impulse measures the integrated force over a period of time that the pipe supports must overcome. As shown in these tables, the peak forces and impulse loading calculated by TREMOLO are generally larger than those calculated using the EPRI TBR methodology. It should be noted, although it was not quantified in this comparison, that the TREMOLO force calculations include the effects of multiple pressure wave reflections and void collapses which would significantly add to the total impulse loadings on the SW piping. The dynamic TREMOLO forcing function histories were used in the piping and piping supports stress calculations. The simplified EPRI-calculated methodology only assumes a single pressure pulse propagated through the SW piping. Based on the comparison of the pipe section forcing functions provided in this assessment, it is concluded that the TREMOLO produced forcing functions generally bound the EPRI-TBR forcing functions for the Point Beach containment fan cooler cooling water supply and return piping.

APPENDIX A

Point Beach CFC 1A EPRI TBR Waterhammer Calculations Using MathCad 2000

POINT BEACH CFC 1A

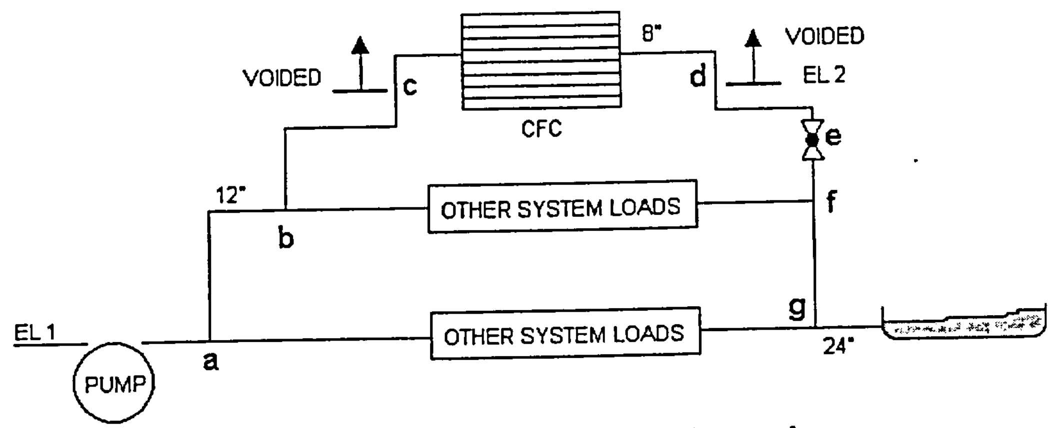


Figure 1 Open Loop Configuration

Pressure & Temperature

Note, pressures listed as "psi" are absolute (psia) or differential (psid) unless otherwise stated

$P_{atm} := 14.7 \cdot psi$	Pressure above reservoir and above heat sink (absolute)
$T_{void} := 224.0 \cdot F$	Temperature in the void when the pumps restart (i.e. surface temperature of piping) [Ref. FAI/97-60 Rev. 3] (Assumed average T in void at 25 sec)
$T_{pipe\_initial} := 75 \cdot F$	Temperature of the fluid and piping when the transient starts [Ref. FAI/97-60 Rev. 3]

Pipe Geometry

$EL_1 := 33.2 \cdot ft$	Elevation of node "1" [Ref. FAI/97-60 Rev. 3]
$EL_2 := 82.3 \cdot ft$	Elevation of node "2" [Ref. FAI/97-60 Rev. 3]
$L_{ab} := 30.5 \cdot ft$	Length from node "a" to node "b" [Ref. FAI/97-60 Rev. 3]
$L_{bc} := 87.5 \cdot ft$	Length from node "b" to node "c" [Ref. FAI/97-60 Rev. 3]
$L_{cd} := 61.4 \cdot ft$	Length from node "c" to node "d" [Ref. FAI/97-60 Rev. 3]
$L_{de} := 78.5 \cdot ft$	Length from node "d" to node "e" [Ref. FAI/97-60 Rev. 3]
$L_{ef} := 4.1 \cdot ft$	Length from node "e" to node "f" [Ref. FAI/97-60 Rev. 3]
$L_{fg} := 87.6 \cdot ft$	Length from node "f" to node "g" [Ref. FAI/97-60 Rev. 3]
$L_{g\_sink} := 400 \cdot ft$	Length from node "g" to the ultimate heat sink [Ref. N/A -not used]
$ID_{abf} := 13.124 \cdot in$	I.D. of piping along path from "a" to "b" to "f" [Ref. FAI/97-60 Rev. 3]
$ID_{bcd} := 7.981 \cdot in$	I.D. of piping along path from "b" to "c" to "d" [Ref. FAI/97-60 Rev. 3]
$ID_{ag} := 22.624 \cdot in$	I.D. of piping along remaining path from "a" to "g" [Ref. FAI/97-60 Rev. 3]
$OD_{bcd} := 8.625 \cdot in$	O.D. of piping along path from "b" to "c" to "d" [Ref. FAI/97-60 Rev. 3]

Flows

$Q_{abf} := 800 \frac{gal}{min}$ Flow along path from "a" to "b" to "f" during steady state condition without voiding [Ref. FAI/97-60 Rev. 3]. Assume other CFC 800 gpm.

$Q_{bcd} := 917 \cdot \frac{gal}{min}$ Flow along path from "b" to "c" to "d" during steady state condition without voiding [Ref. FAI/97-60 Rev. 3]

$Q_{ag} := 5100 \cdot \frac{gal}{min}$ Flow along path from "a" to "g during steady state condition without voiding [Ref. Chuck Richardson Emails dated 1/27/03 & 1/28/03]. Per FSAR nominal flow is 6800 gpm.

FCU Characteristics

$N_{tube} := 240$ Number of tubes in cooler [Ref. FAI/97-60 Rev. 3]

$ID_{tube} := 0.527 \cdot in$ Internal diameter of tubes [Ref. FAI/97-60 Rev. 3]

$L_{tube} := 22 \cdot ft$ Length of tubes [Ref. FAI/97-60 Rev. 3]

Pump Characteristics

$H_s := 240.8 \cdot ft$ Pump shutoff head [Ref. Chuck Richardson Emails dated 1/27/03 & 1/28/03]

$A1 := 0.2547 \cdot \frac{sec}{ft^2}$ 1st order pump curve coefficient [Ref. Chuck Richardson Emails dated 1/27/03 & 1/28/03]

$A2 := -0.5783 \cdot \frac{sec^2}{ft^5}$ 2nd order pump curve coefficient [Ref. Chuck Richardson Emails dated 1/27/03 & 1/28/03]

$Hpump(Qp) := A2 \cdot Qp^2 + A1 \cdot Qp + H_s$ Pump curve equation

Other Inputs

$K_{vlv} := 158.41$ Valve frictional flow coefficient for throttled globe valve [Ref. FAI/97-60 Rev. 3]

$V_{wtr\_fcu} := 0.0 \cdot ft^3$ Volume of water that is left in the FCU when the pump restarts [Ref. FAI/97-60 Rev. 3]

$V_{wtr\_2phase} := 6 \cdot ft^3$ Volume of water that flows into the cooler after voiding has started and before the pumps restart. This volume of water is exposed to two phase flow conditions. [Ref. N/A -not used]

$\rho_{wtr} := 62 \cdot \frac{lb}{ft^3}$ Water density

$T_{des} := 95 \cdot F$ Design temp of the system

$R_{gas} := 1717 \cdot \frac{ft^2}{sec^2 \cdot R}$ Gas constant

Pump Flow Rate Equation

$Qtot_{normal} := Q_{ag} + Q_{bcd} + Q_{abf}$ $\quad$ $H_{norm} := Hpump(Qtot_{normal})$

$Qtot_{normal} = 6\,817 \times 10^3 \frac{gal}{min}$ $\quad$ $H_{norm} = 111\ ft$

The total system flow rate is solved at any pump operating point using:

$$Qpump(Hd) := \frac{-A1 - \sqrt{A1^2 - 4 \cdot A2 \cdot (H_s - Hd)}}{2 \cdot A2}$$

$$Qpump(H_{norm}) = 6.817 \times 10^3 \frac{gal}{min}$$

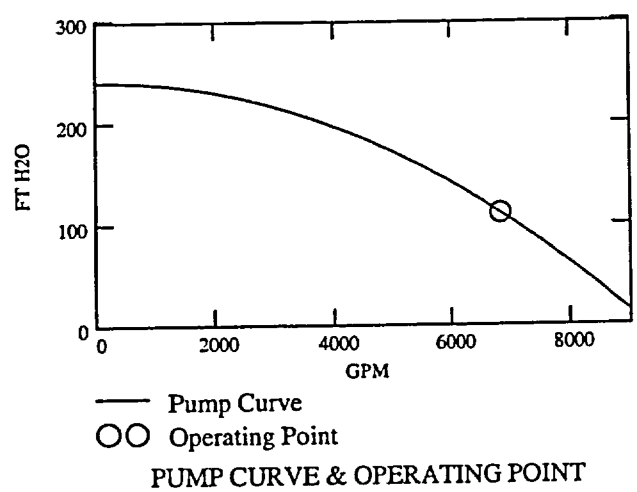


Figure 2 SW Pump Curve

7.4.1 Initial Velocity & FLOW COEFFICIENT PREDICTION

The water at the front of the void (point "d") is assumed to not move or simplification of this problem. More detailed hydraulic modeling may be performed to determine the reverse or forward flow at point "d". In many cases this flow is less than 10% of the incoming flow.

After combining parallel paths the system is then simplified to:

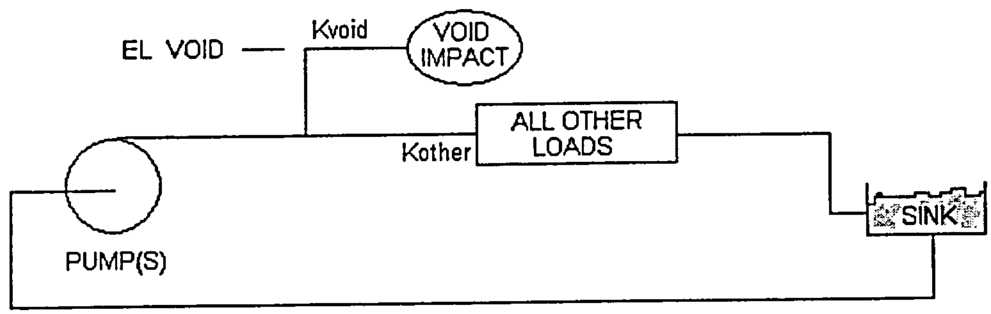


Figure 3 Simplified Open Loop Model

In terms of the initial flow diagram (Figure 1), the flow area for each path is calculated:

$$A_{abf} := \frac{\pi}{4} \cdot ID_{abf}^{\ 2} \qquad A_{bcd} := \frac{\pi}{4} \cdot ID_{bcd}^{\ 2} \qquad A_{ag} := \frac{\pi}{4} \cdot ID_{ag}^{\ 2}$$

$$A_{abf} = 0.939\,ft^2 \qquad A_{bcd} = 0.347\,ft^2 \qquad A_{ag} = 2.792\,ft^2$$

The velocity for each path is calculated:

$$V_{abf} := \frac{Q_{abf}}{A_{abf}} \qquad V_{bcd} := \frac{Q_{bcd}}{A_{bcd}} \qquad V_{ag} := \frac{Q_{ag}}{A_{ag}}$$

$$V_{abf} = 1.9\,\frac{ft}{s} \qquad V_{bcd} = 5.9\,\frac{ft}{s} \qquad V_{ag} = 4.1\,\frac{ft}{s}$$

Calculate equivalent velocity for all other loads:

$$V_{eq} := \frac{Q_{abf} + Q_{ag}}{A_{abf} + A_{ag}}$$

$$V_{eq} = 3.523\,\frac{ft}{s}$$

The flow coefficient for each path is calculated.

The flow resistance from point "a" to point "b" and from point "f" to point "g" are assumed to have a negligible effect on the flow split to the different paths. *In an actual plant system, the engineer may choose to use values from a previously qualified system hydraulic model to determine a more accurate initial velocity.*

$$h_f = K \cdot \frac{V^2}{2 \cdot g} \quad => \quad K = \frac{2 \cdot g \cdot h_f}{V^2}$$

$$K_{abf} := \frac{2 \cdot g \cdot H_{norm}}{V_{abf}^{\ 2}} \qquad K_{bcd} := \frac{2 \cdot g \cdot H_{norm}}{V_{bcd}^{\ 2}} \qquad K_{ag} := \frac{2 \cdot g \cdot H_{norm}}{V_{ag}^{\ 2}}$$

$$K_{abf} = 1.989 \times 10^3 \qquad K_{bcd} = 207 \qquad K_{ag} = 432$$

An equivalent flow coefficient for the "other loads" path (Figure 1) is calculated from:

$$K_{other} := \left(\frac{A_{abf}}{\frac{A_{abf}}{\sqrt{K_{abf}}} + \frac{A_{ag}}{\sqrt{K_{ag}}}} \right)^2 \qquad K_{other} = 37 \qquad A_{other} := A_{abf} \qquad ID_{other} := ID_{abf}$$

An equivalent flow coefficient from all other loads is calculated from:

$$K_{other} := \frac{2 \cdot g \cdot H_{norm}}{V_{eq}^{\ 2}} \qquad A_{other} := A_{abf} + A_{ag}$$

$$K_{other} = 576.797 \qquad ID_{other} := \left(\frac{4 \cdot A_{other}}{\pi} \right)^{0.5} \qquad ID_{other} = 2.18\,\mathrm{ft}$$

The flow coefficient for the path to the void is calculated by subtracting the flow coefficient downstream of the void along this path. To simplify this sample problem only the valve resistance downstream of the void is considered:

$$K_{void} := K_{bcd} - K_{vlv} \qquad K_{void} = 49$$

The pressure in the void is assumed to correspond to the saturation pressure for the void temperature.

$P_{void} := 18.6 \cdot psi$ Absolute pressure based on saturation pressure of Tvoid shown above.
Comes from TREMOLO output. [Ref. FAI/97-60, Rev. 3]

The pump total developed head (TDH) is written by using Bernoulli's equation:

$H_{atm} + EL_1 + TDH = H_{void} + EL_2 + H_f$ where the following terms are defined in terms of feet H2O

H_{atm} = atmospheric pressure head

EL_1 = elevation of node "1"

TDH = total developed head from pump

EL_2 = elevation of node "2"

H_f = frictional losses from point "1" to "2"

The frictional losses are written using Darcy's formula with an appropriate units conversion factor:

$$H_f = 0.00259 \cdot K_{loss} \cdot \frac{Q^2}{ID^4}$$

where

K_{loss} = loss coefficient

Q = flow rate in gpm

ID = pipe diameter in inches

Two equations for the total developed head (TDH) by the pump are written with a corresponding flow balance and initial guesses for the simultaneous solution of these equations:

$Q_{void} := .1$ $\quad Q_{other} := .5$ $\quad TDH := 300$

Given

$$TDH = 0.00259 \cdot K_{other} \cdot \frac{Q_{other}^{\ 2}}{\left(\frac{ID_{other}}{in}\right)^4}$$

frictional losses along "other" path equal the total developed head

$$TDH = 0.00259 \cdot K_{void} \cdot \frac{Q_{void}^{\ 2}}{\left(\frac{ID_{bcd}}{in}\right)^4} + \left(EL_2 - EL_1 - \frac{P_{atm}}{\rho_{wtr} \cdot g} + \frac{P_{void}}{\rho_{wtr} \cdot g}\right) ft^{-1}$$

Bernoulli's along the "void" path

$$Q_{other} + Q_{void} = Qpump(TDH \cdot ft) \cdot \left(\frac{gal}{min}\right)^{-1}$$

pump curve

The solution to the simultaneous equations is solved and defined as "Results".

$Results := Find(TDH, Q_{other}, Q_{void})$

$TDH := Results_0 \cdot ft$ $\quad TDH = 105.207\, ft$

$Q_{other} := Results_1 \cdot \frac{gal}{min}$ $\quad Q_{other} = 5.741 \times 10^3 \frac{gal}{min}$

$Q_{void} := Results_2 \cdot \frac{gal}{min}$ $\quad Q_{void} = 1.231 \times 10^3 \frac{gal}{min}$

The initial velocity is then:

$V_{initial} := \frac{Q_{void}}{A_{bcd}}$ $\quad V_{initial} = 7.9 \frac{ft}{s}$

The total resistance for this path is:

$K_{void} = 49$

Check: is the velocity within the RBM bounds?

$V_{initial}$ < 20 ft/sec ===> yes, velocity is within bounds of RBM runs

7.4.2 VOID & WATER COLUMN LENGTHS

The volume of piping that is voided is calculated:

$$V_{pipe\_voided} := L_{cd} \cdot \frac{\pi}{4} \cdot ID_{bcd}^{2} \qquad V_{pipe\_voided} = 21\,ft^{3}$$

The void of the fan cooler unit is calculated:

$$V_{fcu} := N_{tube} \cdot L_{tube} \cdot \frac{\pi}{4} \cdot ID_{tube}^{2} \qquad V_{fcu} = 8\,ft^{3}$$

The equivalent void length is then:

$$Lao := \frac{V_{pipe\_voided} + V_{fcu}}{A_{bcd}} \qquad Lao = 84\,ft$$

The initial water column length is assumed to be the distance from point "a" to point "c". The discussion that follows explains why point "a" was chosen.

Ignoring the FCU, the flow area changes from the closure point to node "a" are the same as the area changes from the closure point to node "g" on the return side. The transmission coefficients calculated for the return side demonstrate that less than 10% of the pressure pulse propagates to the header. Because of the similar flow area changes, less than 10% of any pressure would propagate into the supply header upstream of point "a". In general, this indicates that the header acts like a large pressurized reservoir during the void closure process and water in the supply header does not add to the inertia of the decelerating water column.

Note: if desired, a plant could select a length all the way back to the pumps. However, this is considered excessively conservative.

The length if the accelerating water column is then:

$$Lwo := L_{ab} + L_{bc} \qquad Lwo = 118\,ft$$

Check: are the lengths within the bounds of the RBM runs?

$Lao < 100$ ft

$Lwo < 400$ ft ===>> yes lengths are within bounds of RBM runs

7.4.3 GAS RELEASE AND MASS OF AIR CONCENTRATED IN VOID

The mass of air concentrated in the void during the void phase of the transient is calculated by assuming that the water that has experienced boiling and subsequent condensation releases its air as described in Section 5 of the User's Manual.

For this problem, the tube volume only will be credited, assuming a draining of the FCU in which the headers do not remain full. This mass of water will release 50% of its non-condensable gas.

$V_{fcu} = 7.998\,ft^3$ or $V_{fcu} = 226\,liter$ from 7.4.2

This represents the mass of water in the tubes which will lose 50% of its non-condensable gas. The concentration of gas is obtained from Figure 5-3.

$T_{des} = 95\,F$

$\frac{T_{des} - 32F}{1.8F} = 35$ deg C

$CON_{air} := 18.5 \frac{mg}{liter}$ From Figure 5-3

$m_{air} := 0.5 \cdot CON_{air} \cdot V_{fcu}$

$m_{air} = 2095\,mg$

Check: is the mass of air within bounds of UM?

for void closure in 8" piping there should be at least 900 mg of air per Table 5.2

===> yes, mass if air is within RBM run bounds.

7.4.4 Cushioned VELOCITY

The graphs presented in Appendix A for the velocity ratios are solutions to the simultaneous differential equations that capture the acceleration of the advancing column and pressurization of the void.

In order to determine the cushioned velocity the following terms that are needed are repeated:

$$V_{initial} = 7.897 \frac{ft}{s}$$

$$K_{void} = 49$$

$$Lao = 84.422\,ft$$

$$Lwo = 118\,ft$$

$$m_{air} = 2.095 \times 10^3\,mg$$

$$T_{void} = 224\,F$$

Check: is the temperature within the bounds of the RBM?
Tvoid > 200 F ===> yes, the temperature is within the RBM run bounds

7.4.4.1 Air Cushioning

If only credit for air cushioning is considered then Figure A-10 from Appendix A is selected. This figure corresponds to 10" piping while the sample problem has 8" piping. 10" piping bounds the 8" piping since the inertia modeled in the 10" piping runs is greater than that in the 8" piping runs and the velocity has reached a steady state until the final void closure occurs. This is apparent by comparison of the 4" and 10" RBM run results for the same gas mass; the velocity is reduced more in the smaller pipe case. ***If the pipe size at a given plant is not shown then the Velocity Ratio chart for the next larger size pipe will always be bounding.***

Figure A-10 corresponds to an initial velocity of 10 fps. The initial velocity calculated in this sample problem is less. The higher velocity chart is selected because the higher momentum associated with the higher velocity bounds the lower velocity. ***If the initial velocity at a plant is not shown then the Velocity Ratio chart for the next larger velocity will always be bounding.***

For a K of 49 as calculated in the sample problem, from Figure A-10 the ratio of the second to initial velocity is:

$$\boxed{\frac{V_{cushion}}{V_{initial}} = 82\%}$$ only air cushion credited

Therefore, the final closure velocity will be reduced by 18% just considering air in this sample problem. Pressure "clipping" is not included here and is calculated later.

7.4.4.2 Air and Steam Cushioning

The velocity that results by considering steam cushioning is found using Figure A-37 from Appendix A. Note that the condensing surface temperature was verified being within the bounds of the RBM run limitations so steam condensation cushioning may be credited. The steam and air cushioning result in a ratio of cushioned to initial velocity of:

$$\boxed{\frac{V_{cushion}}{V_{initial}} = 77\%}$$ air and steam cushioning

The cushioned velocity is then:

$$\boxed{V_{cushion} := 0.77 \cdot V_{initial}} \qquad V_{cushion} = 6.1\,\frac{ft}{s}$$

7.4.5 SONIC VELOCITY

The sonic velocity is calculated from Equation 5-1 and 5-2 in the main body of the User's Manual.

$$P_{void} = 18.6\,psi$$

$$C = \sqrt{\frac{\frac{B}{\rho}}{\left(1 + \frac{B \cdot OD}{E \cdot t}\right)}}$$

where
B=bulk modulus of water $B := 319000psi$
E=Young's modulus for steel
OD=outside diameter of pipe $E := 28 \cdot 10^6 psi$
t=wall thickness

$$C := \sqrt{\frac{\frac{B}{\rho_{wtr}}}{\left[1 + \frac{B \cdot OD_{bcd}}{E \cdot \frac{(OD_{bcd} - ID_{bcd})}{2}}\right]}} \qquad C = 4274\,\frac{ft}{s}$$

7.4.6 PEAK PRESSURE PULSE WITH NO "CLIPPING"

The peak waterhammer pressure is calculated using the Joukowski equation with a coefficient of 1/2 for a water on water closure:

$$\Delta P_{no\_clipping} := \frac{1}{2} \cdot \rho_{wtr} \cdot C \cdot V_{cushion}$$

$$\Delta P_{no\_clipping} = 174\ \mathrm{psi}$$

7.4.7 RISE TIME

The rise time is calculated by using equation 5-4 from the UM.

$$ms := 0.001s$$

$$TR := 0.5sec \cdot \left(\frac{V_{cushion}}{\frac{ft}{sec}} \right)^{-1.3} \qquad TR = 48\ ms$$

7.4.8 TRANSMISSION COEFFICIENTS

The pressure pulse may be affected by rarefaction waves as it is developing and the peak may be "clipped". In addition, the pressure may be attenuated as it propagates through the system as a result of area changes. In order to calculate each of these effects, the transmission coefficients at junctions is required. The transmission coefficients are calculated consistent with section 5.3 of the UM.

At points "f" and "g" the transmission coefficients are calculated using Equation 5-8 from the UM; for simplification here the sonic velocity is assumed to be constant up and downstream of the junction:

$$\tau = \frac{2 \cdot A_{incident}}{A_{incident} + \sum_{j} A_j}$$

$$\tau_f := \frac{2 \cdot A_{bcd}}{A_{bcd} + A_{abf} + A_{abf}} \qquad \tau_f = 0.312$$

=> this fraction of the incident pulse continues past point "f" and the remainder of the incident pulse returns towards the initiation point.

$$\tau_g := \frac{2 \cdot A_{abf}}{A_{abf} + A_{ag} + A_{ag}} \qquad \tau_g = 0.288$$

=> this fraction pulse that is incident upon point "g" continues past point "g" and the remainder of the incident pulse returns towards the initiation point.

$$\tau_{total} := \tau_f \cdot \tau_g$$

$$\tau_{total} = 0.09$$

When the pressure pulse travels past point "g" only 10% of the pulse will continue on. 69% of the incident pulse was reflected as a negative pulse at point "f" and then 71% of the pulse that was incident upon point "g" was reflected back as a negative pulse. The net reflection effect is:

$$\boxed{P_{ref} = P_{inc} \cdot (-69\%) + (31\% \cdot P_{inc}) \cdot (-71\%) = P_{inc}(-69\% - 31\% \cdot 71\%) = 91\%}$$

This reflection travels back to the initiation point. The pulse at the initiation point is 9% of its original value when this reflection arrives. For simplicity, the compounding effect of the "f" node transmission coefficient on the reflected wave from node "g" is ignored.

The transmission coefficient evaluation needs to consider the control valve. The transmission coefficient at the control valve is calculated by assuming the valve acts like an orifice as the pressure pulse propagates through it. Equation 5-14 provides a simple relationship for an orifice flow coefficient in terms of its diameter ratio (β). This equation is used to back calculate an equivalent β ratio for the control valve knowing its coefficient and assuming Co=0.6.

$\beta := 0.5$ Initial guess for the iteration below

$$\beta := \mathrm{root}\left[\left(\frac{1}{0.6 \cdot \beta^2} - 1\right)^2 - K_{vlv}, \beta\right] \qquad \beta = 0.35$$

For this β ratio and for the approximate waterhammer pressure already solved, the control valve will have a slight effect on the pressure pulse propagation by inspection of Figure 5-15. The reflection from this interaction will add approximately 10% to the incident pulse.

In general what this means is that 10% of the pulse magnitude is reflected in a positive sense back towards the initiation point. To account for this effect, the peak pressure pulse is conservatively increased by 10%.

7.4.9 DURATION

The pressure pulse is reduced to approximately 10% of its peak value as a result of the reflections from the area changes at points "f" and "g". As a result, the time that it takes the pressure pulse to travel to point "g" and back may be used to calculate the pressure pulse duration.

$$TD_{eg} := \frac{(L_{de} + L_{ef} + L_{fg}) \cdot 2}{C} \qquad TD_{eg} = 79.7\ \mathrm{ms}$$

Time for pulse to travel to and from point "g". Note that reflections from "a" and "b" are not credited.

The total duration is conservatively increased by adding the rise time.

$$TD := TD_{eg} + TR$$

$$TD = 127\ \mathrm{ms}$$

7.4.10 PRESSURE CLIPPING

The peak pressure is checked for "clipping" using Table 5-3.

$$L_e := L_{de} + L_{ef} + L_{fg} \qquad L_e = 170.2\ \mathrm{ft} \qquad TR \cdot \frac{C}{2} = 102\ \mathrm{ft} \qquad \tau_{total} = 0.09$$

This corresponds to the conditions in row two of the table referenced and no pressure clipping is expected.

$$\boxed{\Delta P := 1.1 \cdot \Delta P_{no\_clipping}}$$

1.1 is from the control valve

$$\Delta P = 191\ \mathrm{psi}$$

7.4.11 PRESSURE PULSE SHAPE

The pulse shape is then characterized by four points.

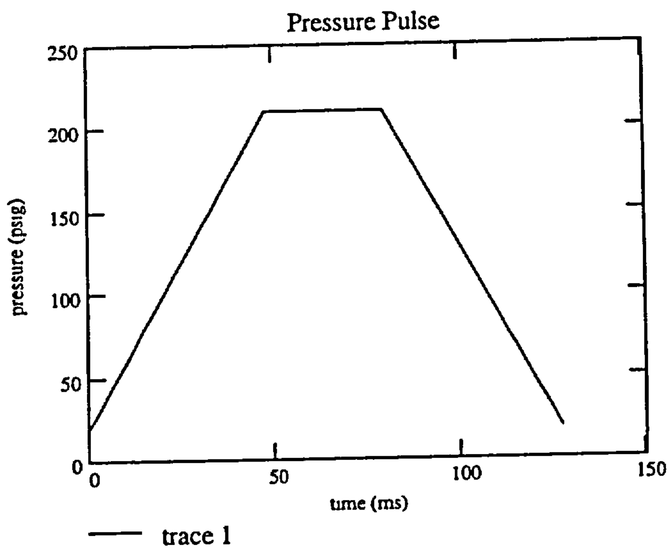
$\boxed{Psys := 19psi}$ this is the steady state system pressure [Ref. FAI/97-60 Rev. 3]

Using an index, i=0,1,2,3 $i := 0..3$

$time_i :=$	$pressure_i :=$
0ms	Psys
TR	$\Delta P + Psys$
TD − TR	$\Delta P + Psys$
TD	Psys

This provides the following values, which are plotted below.

$$time = \begin{pmatrix} 0 \\ 0.048 \\ 0.08 \\ 0.127 \end{pmatrix} s \qquad pressure = \begin{pmatrix} 19 \\ 210 \\ 210 \\ 19 \end{pmatrix} psi$$



Calculate the area underneath the curve to get the pressure impulse:

$$integral := TR \cdot \Delta P + \Delta P \cdot \left(TD_{eg} - TR\right)$$

$$integral = 1.05 \times 10^{5} \frac{kg}{m\,s}$$

$$impulse := integral \cdot A_{bcd} \qquad impulse = 762.175\ lbf \cdot s$$

7.4.12 FLOW AREA ATTENUATION

To simplify the analysis of the SW structures, the approach suggested here is to take the initiating pressure pulse and propagate the pulse through the system. For this example problem, the duration of the pulse is assumed to remain unchanged as it travels. In reality, the duration of the pulse is shortened as it approaches negative reflection sites. Maintaining the duration conservatively increases the impulse.

As the pressure pulse propagates through the system it will be atenuated/amplified by flow area changes. For this example, only the downstream propagation is considered. The pulse will be attenuated by the increase in area at "f" and "g". The transmission coefficients were previously calculated.

incident pulse	pulse transmission	transmitted pulse
$\Delta P = 191\,\text{psi}$	$\Delta P_f := \tau_f \cdot \Delta P$	$\Delta P_f = 60\,\text{psi}$
$\Delta P_f = 60\,\text{psi}$	$\Delta P_g := \tau_g \cdot \Delta P_f$	$\Delta P_g = 17\,\text{psi}$

Downstream of point "g" only the following pulse magnitude will remain: $\Delta P_g = 17\,\text{psi}$

APPENDIX B

Point Beach CFC 1C EPRI TBR Waterhammer Calculations Using MathCad 2000

POINT BEACH CFC 1C

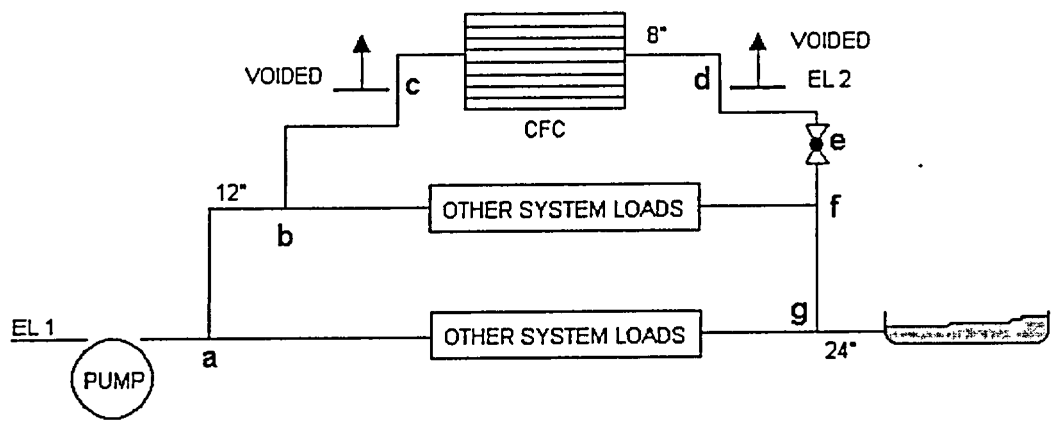


Figure 1 Open Loop Configuration

Pressure & Temperature

Note, pressures listed as "psi" are absolute (psia) or differential (psid) unless otherwise stated

$P_{atm} := 14.7 \cdot psi$	Pressure above reservoir and above heat sink (absolute)
$T_{void} := 223 \cdot F$	Temperature in the void when the pumps restart (i.e. surface temperature of piping) [Ref. FAI/97-60 Rev. 5] (Assumed average T in void at 25 sec)
$T_{pipe\_initial} := 75 \cdot F$	Temperature of the fluid and piping when the transient starts [Ref. FAI/97-60 Rev. 5]

Pipe Geometry

$EL_1 := 33.2 \cdot ft$	Elevation of node "1" [Ref. FAI/97-60 Rev. 5]
$EL_2 := 37.4 \cdot ft$	Elevation of node "2" [Ref. FAI/97-60 Rev. 5]
$L_{ab} := 30.5 \cdot ft$	Length from node "a" to node "b" [Ref. FAI/97-60 Rev. 5]
$L_{bc} := 67.8 \cdot ft$	Length from node "b" to node "c" [Ref. FAI/97-60 Rev. 5]
$L_{cd} := 32.3 \cdot ft$	Length from node "c" to node "d" [Ref. FAI/97-60 Rev. 5]
$L_{de} := 79.8 \cdot ft$	Length from node "d" to node "e" [Ref. FAI/97-60 Rev. 5]
$L_{ef} := 2.2ft$	Length from node "e" to node "f" [Ref. FAI/97-60 Rev. 5]
$L_{fg} := 86.4 \cdot ft$	Length from node "f" to node "g" [Ref. FAI/97-60 Rev. 5]
$L_{g\_sink} := 400 \cdot ft$	Length from node "g" to the ultimate heat sink [Ref. N/A -not used]
$ID_{abf} := 13.124 \cdot in$	I.D. of piping along path from "a" to "b" to "f" [Ref. FAI/97-60 Rev. 5]
$ID_{bcd} := 7.981 \cdot in$	I.D. of piping along path from "b" to "c" to "d" [Ref. FAI/97-60 Rev. 5]
$ID_{ag} := 22.624 \cdot in$	I.D. of piping along remaining path from "a" to "g" [Ref. FAI/97-60 Rev. 5]
$OD_{bcd} := 8.625 \cdot in$	O.D. of piping along path from "b" to "c" to "d" [Ref. FAI/97-60 Rev. 5]

Flows

$Q_{abf} := 800\frac{gal}{min}$ — Flow along path from "a" to "b" to "f" during steady state condition without voiding [Ref. FAI/97-60 Rev. 5]

$Q_{bcd} := 857\cdot\frac{gal}{min}$ — Flow along path from "b" to "c" to "d" during steady state condition without voiding [Ref. FAI/97-60 Rev. 5]

$Q_{ag} := 5200\cdot\frac{gal}{min}$ — Flow along path from "a" to "g during steady state condition without voiding [Ref. Chuck Richardson Emails dated 1/27/03 & 1/28/03]

FCU Characteristics

$N_{tube} := 240$ — Number of tubes in cooler [Ref. FAI/97-60 Rev. 5]

$ID_{tube} := 0.527\cdot in$ — Internal diameter of tubes [Ref. FAI/97-60 Rev. 5]

$L_{tube} := 22\cdot ft$ — Length of tubes [Ref. FAI/97-60 Rev. 5]

Pump Characteristics

$H_s := 240.8\cdot ft$ — Pump shutoff head [Ref. Chuck Richardson Emails dated 1/27/03 & 1/28/03]

$A1 := 0.2547\cdot\frac{sec}{ft^2}$ — 1st order pump curve coefficient [Ref. Chuck Richardson Emails dated 1/27/03 & 1/28/03]

$A2 := -0.5783\cdot\frac{sec^2}{ft^5}$ — 2nd order pump curve coefficient [Ref. Chuck Richardson Emails dated 1/27/03 & 1/28/03]

$Hpump(Qp) := A2\cdot Qp^2 + A1\cdot Qp + H_s$ — Pump curve equation

Other Inputs

$K_{vlv} := 161.472$ — Valve frictional flow coefficient for throttled globe valve [Ref. FAI/97-60 Rev. 5]

$V_{wtr\_fcu} := 0.0\cdot ft^3$ — Volume of water that is left in the FCU when the pump restarts [Ref. FAI/97-60 Rev. 5]

$V_{wtr\_2phase} := 6\cdot ft^3$ — Volume of water that flows into the cooler after voiding has started and before the pumps restart. This volume of water is exposed to two phase flow conditions. [Ref. N/A -not used]

$\rho_{wtr} := 62\cdot\frac{lb}{ft^3}$ — Water density

$T_{des} := 95\cdot F$ — Design temp of the system

$R_{gas} := 1717\cdot\frac{ft^2}{sec^2\cdot R}$ — Gas constant

Pump Flow Rate Equation

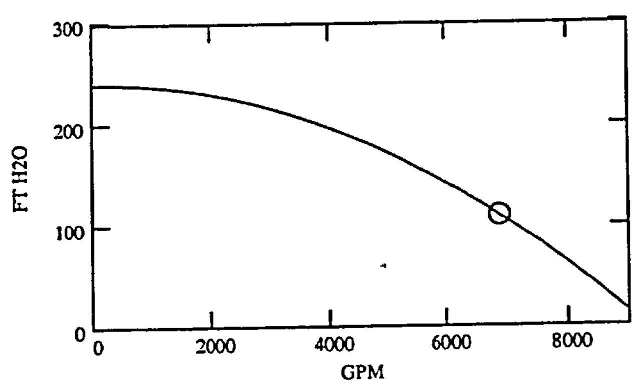
$$Qtot_{normal} := Q_{ag} + Q_{bcd} + Q_{abf} \qquad H_{norm} := Hpump(Qtot_{normal})$$

$$Qtot_{normal} = 6.857 \times 10^3 \frac{gal}{min} \qquad H_{norm} = 110\,ft$$

The total system flow rate is solved at any pump operating point using:

$$Qpump(Hd) := \frac{-A1 - \sqrt{A1^2 - 4 \cdot A2 \cdot (H_s - Hd)}}{2 \cdot A2}$$

$$Qpump(H_{norm}) = 6.857 \times 10^3 \frac{gal}{min}$$



—— Pump Curve
OO Operating Point
PUMP CURVE & OPERATING POINT

Figure 2 SW Pump Curve

7.4.1 Initial Velocity & FLOW COEFFICIENT PREDICTION

The water at the front of the void (point "d") is assumed to not move or simplification of this problem. More detailed hydraulic modeling may be performed to determine the reverse or forward flow at point "d". In many cases this flow is less than 10% of the incoming flow.

After combining parallel paths the system is then simplified to:

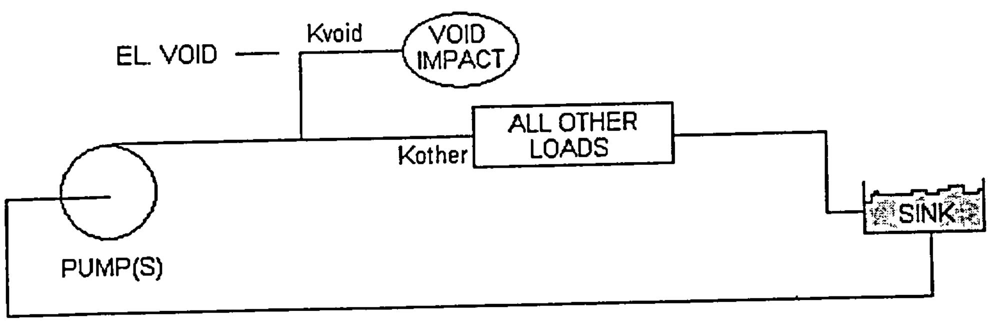


Figure 3 Simplified Open Loop Model

In terms of the initial flow diagram (Figure 1), the flow area for each path is calculated:

$$A_{abf} := \frac{\pi}{4} \cdot ID_{abf}^{2} \qquad A_{bcd} := \frac{\pi}{4} \cdot ID_{bcd}^{2} \qquad A_{ag} := \frac{\pi}{4} \cdot ID_{ag}^{2}$$

$$A_{abf} = 0.939\,ft^2 \qquad A_{bcd} = 0.347\,ft^2 \qquad A_{ag} = 2.792\,ft^2$$

The velocity for each path is calculated:

$$V_{abf} := \frac{Q_{abf}}{A_{abf}} \qquad V_{bcd} := \frac{Q_{bcd}}{A_{bcd}} \qquad V_{ag} := \frac{Q_{ag}}{A_{ag}}$$

$$V_{abf} = 1.9\,\frac{ft}{s} \qquad V_{bcd} = 5.5\,\frac{ft}{s} \qquad V_{ag} = 4.2\,\frac{ft}{s}$$

Calculate equivalent velocity for all other loads:

$$V_{eq} := \frac{Q_{abf} + Q_{ag}}{A_{abf} + A_{ag}}$$

$$V_{eq} = 3.583\,\frac{ft}{s}$$

The flow coefficient for each path is calculated.

The flow resistance from point "a" to point "b" and from point "f" to point "g" are assumed to have a negligible effect on the flow split to the different paths. *In an actual plant system, the engineer may choose to use values from a previously qualified system hydraulic model to determine a more accurate initial velocity.*

$$h_f = K \cdot \frac{V^2}{2 \cdot g} \quad => \quad K = \frac{2 \cdot g \cdot h_f}{V^2}$$

$$K_{abf} := \frac{2 \cdot g \, H_{norm}}{V_{abf}^{\;2}} \qquad K_{bcd} := \frac{2 \cdot g \, H_{norm}}{V_{bcd}^{\;2}} \qquad K_{ag} := \frac{2 \cdot g \cdot H_{norm}}{V_{ag}^{\;2}}$$

$$K_{abf} = 1.961 \times 10^3 \qquad K_{bcd} = 234 \qquad K_{ag} = 410$$

An equivalent flow coefficient for the "other loads" path (Figure 1) is calculated from:

$$K_{other} := \left(\frac{A_{abf}}{\frac{A_{abf}}{\sqrt{K_{abf}}} + \frac{A_{ag}}{\sqrt{K_{ag}}}} \right)^2 \qquad K_{other} = 35 \qquad A_{other} := A_{abf} \qquad ID_{other} := ID_{abf}$$

An equivalent flow coefficient from all other loads is calculated from:

$$K_{other} := \frac{2 \cdot g \cdot H_{norm}}{V_{eq}^{\;2}} \qquad A_{other} := A_{abf} + A_{ag}$$

$$K_{other} = 549.974 \qquad ID_{other} := \left(\frac{4 \cdot A_{other}}{\pi} \right)^{0.5} \qquad ID_{other} = 2.18\,\text{ft}$$

The flow coefficient for the path to the void is calculated by subtracting the flow coefficient downstream of the void along this path. To simplify this sample problem only the valve resistance downstream of the void is considered:

$$K_{void} := K_{bcd} - K_{vlv} \qquad K_{void} = 72$$

The pressure in the void is assumed to correspond to the saturation pressure for the void temperature.

$P_{void} := 18.3 \cdot \text{psi}$ Absolute pressure based on saturation pressure of Tvoid shown above.
Comes from TREMOLO output. [Ref. FAI/97-60, Rev. 5]

The pump total developed head (TDH) is written by using Bernoulli's equation:

$$H_{atm} + EL_1 + TDH = H_{void} + EL_2 + H_f$$

where the following terms are defined in terms of feet H2O

H_{atm} = atmospheric pressure head

EL_1 = elevation of node "1"

TDH = total developed head from pump

EL_2 = elevation of node "2"

H_f = frictional losses from point "1" to "2"

The frictional losses are written using Darcy's formula with an appropriate units conversion factor:

$$H_f = 0.00259 \cdot K_{loss} \cdot \frac{Q^2}{ID^4}$$

where

K_{loss} = loss coefficient

Q = flow rate in gpm

ID = pipe diameter in inches

Two equations for the total developed head (TDH) by the pump are written with a corresponding flow balance and initial guesses for the simultaneous solution of these equations:

$Q_{void} := .1$ $\quad Q_{other} := .5$ $\quad TDH := 300$

Given

$$TDH = 0.00259 \cdot K_{other} \cdot \frac{Q_{other}^{\;2}}{\left(\frac{ID_{other}}{in}\right)^4}$$

frictional losses along "other" path equal the total developed head

$$TDH = 0.00259 \cdot K_{void} \cdot \frac{Q_{void}^{\;2}}{\left(\frac{ID_{bcd}}{in}\right)^4} + \left(EL_2 - EL_1 - \frac{P_{atm}}{\rho_{wtr} \cdot g} + \frac{P_{void}}{\rho_{wtr} \cdot g}\right) ft^{-1}$$

Bernoulli's along the "void" path

$$Q_{other} + Q_{void} = Qpump(TDH \cdot ft) \cdot \left(\frac{gal}{min}\right)^{-1}$$

pump curve

The solution to the simultaneous equations is solved and defined as "Results".

$Results := Find(TDH, Q_{other}, Q_{void})$

$TDH := Results_0 \cdot ft$ $\quad TDH = 99.906\,ft$

$Q_{other} := Results_1 \cdot \frac{gal}{min}$ $\quad Q_{other} = 5.729 \times 10^3 \frac{gal}{min}$

$Q_{void} := Results_2 \cdot \frac{gal}{min}$ $\quad Q_{void} = 1.376 \times 10^3 \frac{gal}{min}$

The initial velocity is then:

$V_{initial} := \frac{Q_{void}}{A_{bcd}}$ $\quad V_{initial} = 8.8 \frac{ft}{s}$

The total resistance for this path is:

$K_{void} = 72$

Check: is the velocity within the RBM bounds?

$V_{initial}$ < 20 ft/sec ===> yes, velocity is within bounds of RBM runs

7.4.2 VOID & WATER COLUMN LENGTHS

The volume of piping that is voided is calculated:

$$V_{pipe\_voided} := L_{cd} \cdot \frac{\pi}{4} \cdot ID_{bcd}^{2} \qquad V_{pipe\_voided} = 11\,ft^3$$

The void of the fan cooler unit is calculated:

$$V_{fcu} := N_{tube} \cdot L_{tube} \cdot \frac{\pi}{4} ID_{tube}^{2} \qquad V_{fcu} = 8\,ft^3$$

The equivalent void length is then:

$$Lao := \frac{V_{pipe\_voided} + V_{fcu}}{A_{bcd}} \qquad Lao = 55\,ft$$

The initial water column length is assumed to be the distance from point "a" to point "c". The discussion that follows explains why point "a" was chosen.

Ignoring the FCU, the flow area changes from the closure point to node "a" are the same as the area changes from the closure point to node "g" on the return side. The transmission coefficients calculated for the return side demonstrate that less than 10% of the pressure pulse propagates to the header. Because of the similar flow area changes, less than 10% of any pressure would propagate into the supply header upstream of point "a". In general, this indicates that the header acts like a large pressurized reservoir during the void closure process and water in the supply header does not add to the inertia of the decelerating water column.

Note: if desired, a plant could select a length all the way back to the pumps. However, this is considered excessively conservative.

The length if the accelerating water column is then:

$$Lwo := L_{ab} + L_{bc} \qquad Lwo = 98.3\,ft$$

Check: are the lengths within the bounds of the RBM runs?

Lao < 100 ft

Lwo < 400 ft ===>> yes lengths are within bounds of RBM runs

7.4.3 GAS RELEASE AND MASS OF AIR CONCENTRATED IN VOID

The mass of air concentrated in the void during the void phase of the transient is calculated by assuming that the water that has experienced boiling and subsequent condensation releases its air as described in Section 5 of the User's Manual.

For this problem, the tube volume only will be credited, assuming a draining of the FCU in which the headers do not remain full. This mass of water will release 50% of its non-condensable gas.

$V_{fcu} = 7.998\,ft^3$ or $V_{fcu} = 226\,liter$ from 7.4.2

This represents the mass of water in the tubes which will lose 50% of its non-condensable gas. The concentration of gas is obtained from Figure 5-3.

$T_{des} = 95\,F$

$\frac{T_{des} - 32F}{1.8F} = 35$ deg C

$CON_{air} := 18.5 \frac{mg}{liter}$ From Figure 5-3

$m_{air} := 0.5 \cdot CON_{air} \cdot V_{fcu}$

$m_{air} = 2095\,mg$

Check: is the mass of air within bounds of UM?

for void closure in 8" piping there should be at least 900 mg of air per Table 5.2

===> yes, mass if air is within RBM run bounds.

7.4.4 Cushioned VELOCITY

The graphs presented in Appendix A for the velocity ratios are solutions to the simultaneous differential equations that capture the acceleration of the advancing column and pressurization of the void.

In order to determine the cushioned velocity the following terms that are needed are repeated:

$$V_{initial} = 8.826 \frac{ft}{s}$$

$$K_{void} = 72$$

$$Lao = 55.322\,ft$$

$$Lwo = 98.3\,ft$$

$$m_{air} = 2.095 \times 10^{3}\,mg$$

$$T_{void} = 223\,F$$

Check: is the temperature within the bounds of the RBM?
Tvoid > 200 F ===> yes, the temperature is within the RBM run bounds

7.4.4.1 Air Cushioning

If only credit for air cushioning is considered then Figure A-10 from Appendix A is selected. This figure corresponds to 10" piping while the sample problem has 8" piping. 10" piping bounds the 8" piping since the inertia modeled in the 10" piping runs is greater than that in the 8" piping runs and the velocity has reached a steady state until the final void closure occurs. This is apparent by comparison of the 4" and 10" RBM run results for the same gas mass; the velocity is reduced more in the smaller pipe case. ***If the pipe size at a given plant is not shown then the Velocity Ratio chart for the next larger size pipe will always be bounding.***

Figure A-10 corresponds to an initial velocity of 10 fps. The initial velocity calculated in this sample problem is less. The higher velocity chart is selected because the higher momentum associated with the higher velocity bounds the lower velocity. ***If the initial velocity at a plant is not shown then the Velocity Ratio chart for the next larger velocity will always be bounding.***

For a K of 72 as calculated in the sample problem, from Figure A-10 the ratio of the second to initial velocity is:

$$\boxed{\frac{V_{cushion}}{V_{initial}} = 83\%}$$ only air cushion credited

Therefore, the final closure velocity will be reduced by 17% just considering air in this sample problem. Pressure "clipping" is not included here and is calculated later.

7.4.4.2 Air and Steam Cushioning

The velocity that results by considering steam cushioning is found using Figure A-37 from Appendix A. Note that the condensing surface temperature was verified being within the bounds of the RBM run limitations so steam condensation cushioning may be credited. The steam and air cushioning result in a ratio of cushioned to initial velocity of:

$$\boxed{\frac{V_{cushion}}{V_{initial}} = 80\%}$$ air and steam cushioning

The cushioned velocity is then:

$$\boxed{V_{cushion} := 0.80 \cdot V_{initial}} \qquad V_{cushion} = 7.1 \frac{ft}{s}$$

7.4.5 SONIC VELOCITY

The sonic velocity is calculated from Equation 5-1 and 5-2 in the main body of the User's Manual.

$$P_{void} = 18.3\,psi$$

$$C = \sqrt{\frac{\frac{B}{\rho}}{\left(1 + \frac{B \cdot OD}{E \cdot t}\right)}}$$

where
B=bulk modulus of water $B := 319000psi$
E=Young's modulus for steel
OD=outside diameter of pipe $E := 28 \cdot 10^6 psi$
t=wall thickness

$$C := \sqrt{\frac{\frac{B}{\rho_{wtr}}}{\left[1 + \frac{B \cdot OD_{bcd}}{E \cdot \frac{(OD_{bcd} - ID_{bcd})}{2}}\right]}} \qquad C = 4274 \frac{ft}{s}$$

7.4.6 PEAK PRESSURE PULSE WITH NO "CLIPPING"

The peak waterhammer pressure is calculated using the Joukowski equation with a coefficient of 1/2 for a water on water closure:

$$\Delta P_{no\_clipping} := \frac{1}{2} \cdot \rho_{wtr} \cdot C \cdot V_{cushion}$$

$$\Delta P_{no\_clipping} = 202\,\mathrm{psi}$$

7.4.7 RISE TIME

The rise time is calculated by using equation 5-4 from the UM.

$$ms := 0.001s$$

$$TR := 0.5sec \cdot \left(\frac{V_{cushion}}{\frac{ft}{sec}} \right)^{-1.3} \qquad TR = 39\,ms$$

7.4.8 TRANSMISSION COEFFICIENTS

The pressure pulse may be affected by rarefaction waves as it is developing and the peak may be "clipped". In addition, the pressure may be attenuated as it propagates through the system as a result of area changes. In order to calculate each of these effects, the transmission coefficients at junctions is required. The transmission coefficients are calculated consistent with section 5.3 of the UM.

At points "f" and "g" the transmission coefficients are calculated using Equation 5-8 from the UM; for simplification here the sonic velocity is assumed to be constant up and downstream of the junction:

$$\tau = \frac{2 \cdot A_{incident}}{A_{incident} + \sum_{j} A_j}$$

$$\tau_f := \frac{2 \cdot A_{bcd}}{A_{bcd} + A_{abf} + A_{abf}}$$

$\tau_f = 0.312$ => this fraction of the incident pulse continues past point "f" and the remainder of the incident pulse returns towards the initiation point.

$$\tau_g := \frac{2 \cdot A_{abf}}{A_{abf} + A_{ag} + A_{ag}}$$

$\tau_g = 0.288$ => this fraction pulse that is incident upon point "g" continues past point "g" and the remainder of the incident pulse returns towards the initiation point.

$$\tau_{total} := \tau_f \cdot \tau_g$$

$$\tau_{total} = 0.09$$

When the pressure pulse travels past point "g" only 10% of the pulse will continue on. 69% of the incident pulse was reflected as a negative pulse at point "f" and then 71% of the pulse that was incident upon point "g" was reflected back as a negative pulse. The net reflection effect is:

$$\boxed{P_{ref} = P_{inc} \cdot (-69\%) + (31\% \cdot P_{inc}) \cdot (-71\%) = P_{inc}(-69\% - 31\% \cdot 71\%) = 91\%}$$

This reflection travels back to the initiation point. The pulse at the initiation point is 9% of its original value when this reflection arrives. For simplicity, the compounding effect of the "f" node transmission coefficient on the reflected wave from node "g" is ignored.

The transmission coefficient evaluation needs to consider the control valve. The transmission coefficient at the control valve is calculated by assuming the valve acts like an orifice as the pressure pulse propagates through it. Equation 5-14 provides a simple relationship for an orifice flow coefficient in terms of its diameter ratio (β). This equation is used to back calculate an equivalent β ratio for the control valve knowing its coefficient and assuming Co=0.6.

$\beta := 0.5$ Initial guess for the iteration below

$$\beta := \mathrm{root}\left[\left(\frac{1}{0.6 \cdot \beta^2} - 1\right)^2 - K_{vlv}, \beta\right] \qquad \beta = 0.349$$

For this β ratio and for the approximate waterhammer pressure already solved, the control valve will have a slight effect on the pressure pulse propagation by inspection of Figure 5-15. The reflection from this interaction will add approximately 10% to the incident pulse.

In general what this means is that 10% of the pulse magnitude is reflected in a positive sense back towards the initiation point. To account for this effect, the peak pressure pulse is conservatively increased by 10%.

7.4.9 DURATION

The pressure pulse is reduced to approximately 10% of its peak value as a result of the reflections from the area changes at points "f" and "g". As a result, the time that it takes the pressure pulse to travel to point "g" and back may be used to calculate the pressure pulse duration.

$$TD_{eg} := \frac{(L_{de} + L_{ef} + L_{fg}) \cdot 2}{C} \qquad TD_{eg} = 78.8\,\text{ms}$$

Time for pulse to travel to and from point "g". Note that reflections from "a" and "b" are not credited.

The total duration is conservatively increased by adding the rise time.

$$TD := TD_{eg} + TR$$

$$TD = 118\,\text{ms}$$

7.4.10 PRESSURE CLIPPING

The peak pressure is checked for "clipping" using Table 5-3.

$$L_e := L_{de} + L_{ef} + L_{fg} \qquad L_e = 168.4\,\text{ft} \qquad TR \cdot \frac{C}{2} = 84\,\text{ft} \qquad \tau_{total} = 0.09$$

This corresponds to the conditions in row two of the table referenced and no pressure clipping is expected.

$$\boxed{\Delta P := 1.1 \cdot \Delta P_{no\_clipping}}$$

1.1 is from the control valve

$$\Delta P = 222\,\text{psi}$$

7.4.11 PRESSURE PULSE SHAPE

The pulse shape is then characterized by four points.

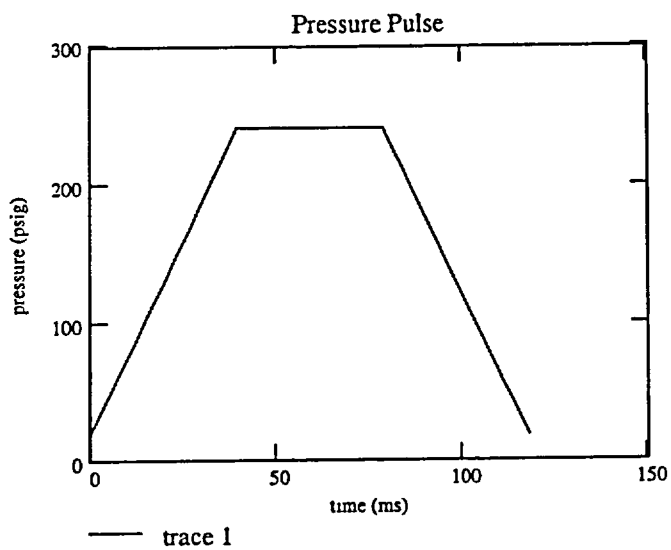
$\boxed{Psys := 19psi}$ this is the steady state system pressure [Ref. FAI/97-60 Rev. 5]

Using an index, i=0,1,2,3 $i := 0..3$

$time_i :=$	$pressure_i :=$
0ms	Psys
TR	$\Delta P + Psys$
TD − TR	$\Delta P + Psys$
TD	Psys

This provides the following values, which are plotted below.

$$time = \begin{pmatrix} 0 \\ 0.039 \\ 0.079 \\ 0.118 \end{pmatrix} s \qquad pressure = \begin{pmatrix} 19 \\ 241 \\ 241 \\ 19 \end{pmatrix} psi$$



Calculate the area underneath the curve to get the pressure impulse:

$$integral := TR \cdot \Delta P + \Delta P \cdot \left(TD_{eg} - TR\right)$$

$$integral = 1.207 \times 10^{5} \frac{kg}{m\,s}$$

$impulse := integral \cdot A_{bcd}$ $\qquad$ $impulse = 875.596\,lbf \cdot s$

7.4.12 FLOW AREA ATTENUATION

To simplify the analysis of the SW structures, the approach suggested here is to take the initiating pressure pulse and propagate the pulse through the system. For this example problem, the duration of the pulse is assumed to remain unchanged as it travels. In reality, the duration of the pulse is shortened as it approaches negative reflection sites. Maintaining the duration conservatively increases the impulse.

As the pressure pulse propagates through the system it will be atenuated/amplified by flow area changes. For this example, only the downstream propagation is considered. The pulse will be attenuated by the increase in area at "f" and "g". The transmission coefficients were previously calculated.

incident pulse	pulse transmission	transmitted pulse
$\Delta P = 222\,\text{psi}$	$\Delta P_f := \tau_f \cdot \Delta P$	$\Delta P_f = 69\,\text{psi}$
$\Delta P_f = 69\,\text{psi}$	$\Delta P_g := \tau_g \cdot \Delta P_f$	$\Delta P_g = 20\,\text{psi}$

Downstream of point "g" only the following pulse magnitude will remain: $\Delta P_g = 20\,\text{psi}$

APPENDIX C

Point Beach CFC 2B EPRI TBR Waterhammer Calculations Using MathCad 2000

POINT BEACH CFC 2B

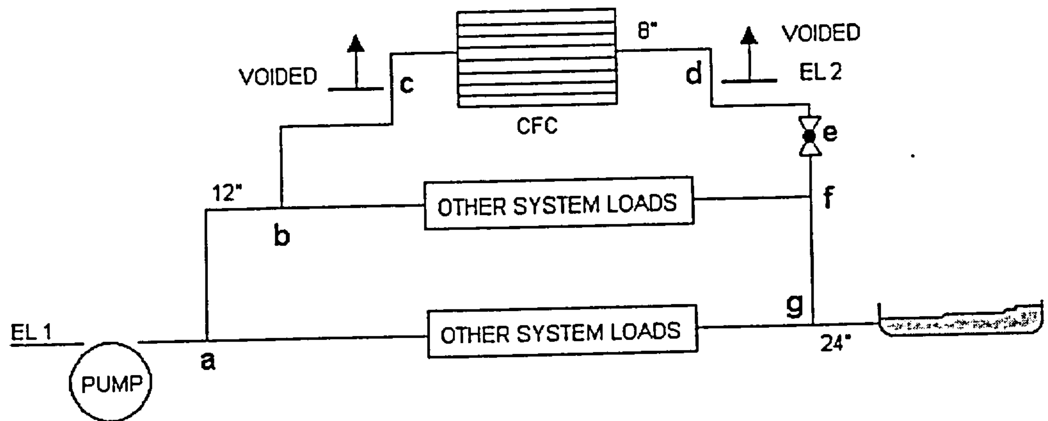


Figure 1 Open Loop Configuration

Pressure & Temperature

Note, pressures listed as "psi" are absolute (psia) or differential (psid) unless otherwise stated

$P_{atm} := 14.7 \cdot psi$	Pressure above reservoir and above heat sink (absolute)
$T_{void} := 217.1 \cdot F$	Temperature in the void when the pumps restart (i.e. surface temperature of piping) [Ref. FAI/97-60 Rev. 2] (Assumed average T in void at 26 sec)
$T_{pipe\_initial} := 75 \cdot F$	Temperature of the fluid and piping when the transient starts [Ref. FAI/97-60 Rev. 2]

Pipe Geometry

$EL_1 := 33.2 \cdot ft$	Elevation of node "1" [Ref. FAI/97-60 Rev. 2]
$EL_2 := 72.0 \cdot ft$	Elevation of node "2" [Ref. FAI/97-60 Rev. 2]
$L_{ab} := 36.8 \cdot ft$	Length from node "a" to node "b" [Ref. FAI/97-60 Rev. 2]
$L_{bc} := 139.4 \cdot ft$	Length from node "b" to node "c" [Ref. FAI/97-60 Rev. 2]
$L_{cd} := 83.6 \cdot ft$	Length from node "c" to node "d" [Ref. FAI/97-60 Rev. 2]
$L_{de} := 129.2 \cdot ft$	Length from node "d" to node "e" [Ref. FAI/97-60 Rev. 2]
$L_{ef} := 4.8 \cdot ft$	Length from node "e" to node "f" [Ref. FAI/97-60 Rev. 2]
$L_{fg} := 118.6 \cdot ft$	Length from node "f" to node "g" [Ref. FAI/97-60 Rev. 2]
$L_{g\_sink} := 400 \cdot ft$	Length from node "g" to the ultimate heat sink [Ref. N/A -not used]
$ID_{abf} := 13.124 \cdot in$	I.D. of piping along path from "a" to "b" to "f" [Ref. FAI/97-60 Rev. 2]
$ID_{bcd} := 7.981 \cdot in$	I.D. of piping along path from "b" to "c" to "d" [Ref. FAI/97-60 Rev. 2]
$ID_{ag} := 22.624 \cdot in$	I.D. of piping along remaining path from "a" to "g" [Ref. FAI/97-60 Rev. 2]
$OD_{bcd} := 8.625 \cdot in$	O.D. of piping along path from "b" to "c" to "d" [Ref. FAI/97-60 Rev. 2]

Flows

$Q_{abf} := 800 \frac{gal}{min}$	Flow along path from "a" to "b" to "f" during steady state condition without voiding [Ref. FAI/97-60 Rev. 2]
$Q_{bcd} := 886 \cdot \frac{gal}{min}$	Flow along path from "b" to "c" to "d" during steady state condition without voiding [Ref. FAI/97-60 Rev. 2]
$Q_{ag} := 5200 \cdot \frac{gal}{min}$	Flow along path from "a" to "g during steady state condition without voiding [Ref. Chuck Richardson Emails dated 1/27/03 & 1/28/03]

FCU Characteristics

$N_{tube} := 240$	Number of tubes in cooler [Ref. FAI/97-60 Rev. 2]
$ID_{tube} := 0.527 \cdot in$	Internal diameter of tubes [Ref. FAI/97-60 Rev. 2]
$L_{tube} := 22 \cdot ft$	Length of tubes [Ref. FAI/97-60 Rev. 2]

Pump Characteristics

$H_s := 240.8 \cdot ft$	Pump shutoff head [Ref. Chuck Richardson Emails dated 1/27/03 & 1/28/03]
$A1 := 0.2547 \cdot \frac{sec}{ft^2}$	1st order pump curve coefficient [Ref. Chuck Richardson Emails dated 1/27/03 & 1/28/03]
$A2 := -0.5783 \cdot \frac{sec^2}{ft^5}$	2nd order pump curve coefficient [Ref. Chuck Richardson Emails dated 1/27/03 & 1/28/03]

$Hpump(Qp) := A2 \cdot Qp^2 + A1 \cdot Qp + H_s$ Pump curve equation

Other Inputs

$K_{vlv} := 165.447$	Valve frictional flow coefficient for throttled globe valve [Ref. FAI/97-60 Rev. 2]
$V_{wtr\_fcu} := 0.0\ ft^3$	Volume of water that is left in the FCU when the pump restarts [Ref. FAI/97-60 Rev. 2]
$V_{wtr\_2phase} := 6 \cdot ft^3$	Volume of water that flows into the cooler after voiding has started and before the pumps restart. This volume of water is exposed to two phase flow conditions. [Ref. N/A -not used]
$\rho_{wtr} := 62 \cdot \frac{lb}{ft^3}$	Water density
$T_{des} := 95 \cdot F$	Design temp of the system
$R_{gas} := 1717 \cdot \frac{ft^2}{sec^2 \cdot R}$	Gas constant

Pump Flow Rate Equation

$$Qtot_{normal} := Q_{ag} + Q_{bcd} + Q_{abf} \qquad H_{norm} := Hpump\left(Qtot_{normal}\right)$$

$$Qtot_{normal} = 6.886 \times 10^{3} \frac{gal}{min} \qquad H_{norm} = 109\,ft$$

The total system flow rate is solved at any pump operating point using:

$$Qpump(Hd) := \frac{-A1 - \sqrt{A1^{2} - 4 \cdot A2 \cdot \left(H_{s} - Hd\right)}}{2 \cdot A2}$$

$$Qpump\left(H_{norm}\right) = 6.886 \times 10^{3} \frac{gal}{min}$$

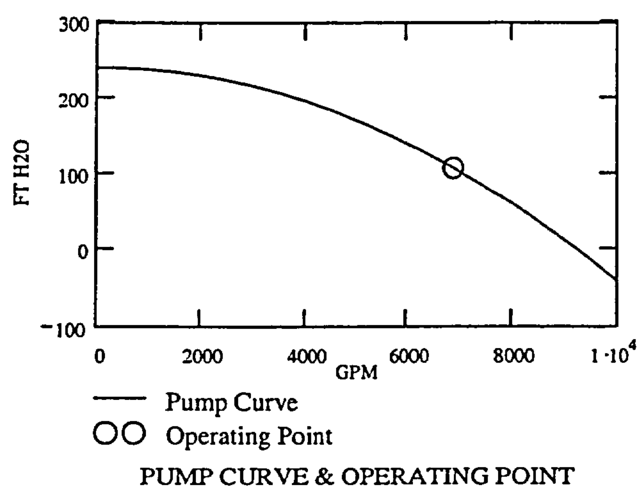


Figure 2 SW Pump Curve

7.4.1 Initial Velocity & FLOW COEFFICIENT PREDICTION

The water at the front of the void (point "d") is assumed to not move or simplification of this problem. More detailed hydraulic modeling may be performed to determine the reverse or forward flow at point "d". In many cases this flow is less than 10% of the incoming flow.

After combining parallel paths the system is then simplified to:

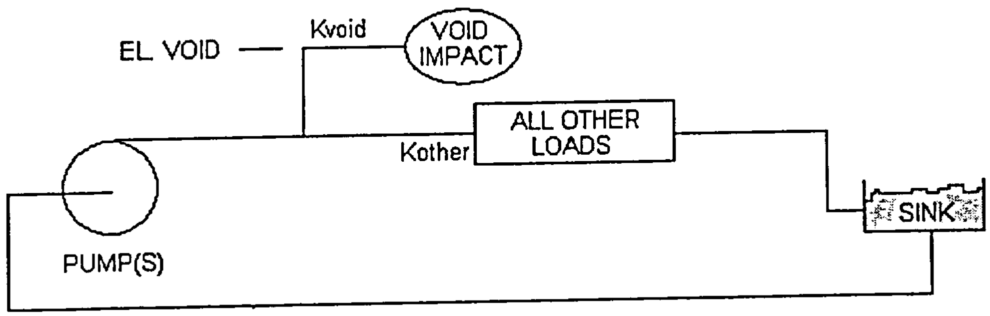


Figure 3 Simplified Open Loop Model

In terms of the initial flow diagram (Figure 1), the flow area for each path is calculated:

$$A_{abf} := \frac{\pi}{4} \cdot ID_{abf}^{2} \qquad A_{bcd} := \frac{\pi}{4} \cdot ID_{bcd}^{2} \qquad A_{ag} := \frac{\pi}{4} \cdot ID_{ag}^{2}$$

$$A_{abf} = 0.939\,ft^2 \qquad A_{bcd} = 0.347\,ft^2 \qquad A_{ag} = 2.792\,ft^2$$

The velocity for each path is calculated:

$$V_{abf} := \frac{Q_{abf}}{A_{abf}} \qquad V_{bcd} := \frac{Q_{bcd}}{A_{bcd}} \qquad V_{ag} := \frac{Q_{ag}}{A_{ag}}$$

$$V_{abf} = 1.9\,\frac{ft}{s} \qquad V_{bcd} = 5.7\,\frac{ft}{s} \qquad V_{ag} = 4.2\,\frac{ft}{s}$$

Calculate equivalent velocity for all other loads:

$$V_{eq} := \frac{Q_{abf} + Q_{ag}}{A_{abf} + A_{ag}}$$

$$V_{eq} = 3.583\,\frac{ft}{s}$$

The flow coefficient for each path is calculated.

The flow resistance from point "a" to point "b" and from point "f" to point "g" are assumed to have a negligible effect on the flow split to the different paths. *In an actual plant system, the engineer may choose to use values from a previously qualified system hydraulic model to determine a more accurate initial velocity.*

$$h_f = K \cdot \frac{V^2}{2 \cdot g} \quad \Rightarrow \quad K = \frac{2 \cdot g \cdot h_f}{V^2}$$

$$K_{abf} := \frac{2 \cdot g \cdot H_{norm}}{V_{abf}^{\ 2}} \qquad K_{bcd} := \frac{2 \cdot g \cdot H_{norm}}{V_{bcd}^{\ 2}} \qquad K_{ag} := \frac{2 \cdot g \cdot H_{norm}}{V_{ag}^{\ 2}}$$

$$K_{abf} = 1.941 \times 10^3 \qquad K_{bcd} = 216 \qquad K_{ag} = 406$$

An equivalent flow coefficient for the "other loads" path (Figure 1) is calculated from:

$$K_{other} := \left(\frac{A_{abf}}{\frac{A_{abf}}{\sqrt{K_{abf}}} + \frac{A_{ag}}{\sqrt{K_{ag}}}} \right)^2 \qquad K_{other} = 35 \qquad A_{other} := A_{abf} \qquad ID_{other} := ID_{abf}$$

An equivalent flow coefficient from all other loads is calculated from:

$$K_{other} := \frac{2 \cdot g \cdot H_{norm}}{V_{eq}^{\ 2}} \qquad A_{other} := A_{abf} + A_{ag}$$

$$K_{other} = 544.321 \qquad ID_{other} := \left(\frac{4 \cdot A_{other}}{\pi} \right)^{0.5} \qquad ID_{other} = 2.18\,\text{ft}$$

The flow coefficient for the path to the void is calculated by subtracting the flow coefficient downstream of the void along this path. To simplify this sample problem only the valve resistance downstream of the void is considered:

$$K_{void} := K_{bcd} - K_{vlv} \qquad K_{void} = 51$$

The pressure in the void is assumed to correspond to the saturation pressure for the void temperature.

$P_{void} := 16.3 \cdot psi$ Absolute pressure based on saturation pressure of Tvoid shown above.
Comes from TREMOLO output. [Ref. FAI/97-60, Rev. 2]

The pump total developed head (TDH) is written by using Bernoulli's equation:

$H_{atm} + EL_1 + TDH = H_{void} + EL_2 + H_f$ where the following terms are defined in terms of feet H2O

H_{atm} = atmospheric pressure head
EL_1 = elevation of node "1"
TDH = total developed head from pump
EL_2 = elevation of node "2"
H_f = frictional losses from point "1" to "2"

The frictional losses are written using Darcy's formula with an appropriate units conversion factor:

$$H_f = 0.00259 \cdot K_{loss} \cdot \frac{Q^2}{ID^4}$$

where
K_{loss} = loss coefficient
Q = flow rate in gpm
ID = pipe diameter in inches

Two equations for the total developed head (TDH) by the pump are written with a corresponding flow balance and initial guesses for the simultaneous solution of these equations:

$Q_{void} := .1$ $\quad Q_{other} := .5$ $\quad TDH := 300$

Given

$$TDH = 0.00259 \cdot K_{other} \cdot \frac{Q_{other}^2}{\left(\frac{ID_{other}}{in}\right)^4}$$

frictional losses along "other" path equal the total developed head

$$TDH = 0.00259 \cdot K_{void} \cdot \frac{Q_{void}^2}{\left(\frac{ID_{bcd}}{in}\right)^4} + \left(EL_2 - EL_1 - \frac{P_{atm}}{\rho_{wtr} \cdot g} + \frac{P_{void}}{\rho_{wtr} \cdot g}\right) ft^{-1}$$

Bernoulli's along the "void" path

$$Q_{other} + Q_{void} = Qpump(TDH \cdot ft) \cdot \left(\frac{gal}{min}\right)^{-1}$$

pump curve

The solution to the simultaneous equations is solved and defined as "Results".

$Results := Find(TDH, Q_{other}, Q_{void})$

$TDH := Results_0 \cdot ft$ $\quad TDH = 100.189\ ft$

$Q_{other} := Results_1 \cdot \frac{gal}{min}$ $\quad Q_{other} = 5.767 \times 10^3 \frac{gal}{min}$

$Q_{void} := Results_2 \cdot \frac{gal}{min}$ $\quad Q_{void} = 1.331 \times 10^3 \frac{gal}{min}$

The initial velocity is then:

$V_{initial} := \frac{Q_{void}}{A_{bcd}}$ $\quad V_{initial} = 8.5 \frac{ft}{s}$

The total resistance for this path is:

$K_{void} = 51$

Check: is the velocity within the RBM bounds?

$V_{initial}$ < 20 ft/sec ===> yes, velocity is within bounds of RBM runs

7.4.2 VOID & WATER COLUMN LENGTHS

The volume of piping that is voided is calculated:

$$V_{pipe\_voided} := L_{cd} \cdot \frac{\pi}{4} \cdot ID_{bcd}{}^{2} \qquad V_{pipe\_voided} = 29\,ft^{3}$$

The void of the fan cooler unit is calculated:

$$V_{fcu} := N_{tube} \cdot L_{tube} \cdot \frac{\pi}{4} \cdot ID_{tube}{}^{2} \qquad V_{fcu} = 8\,ft^{3}$$

The equivalent void length is then:

$$Lao := \frac{V_{pipe\_voided} + V_{fcu}}{A_{bcd}} \qquad Lao = 107\,ft$$

The initial water column length is assumed to be the distance from point "a" to point "c". The discussion that follows explains why point "a" was chosen.

Ignoring the FCU, the flow area changes from the closure point to node "a" are the same as the area changes from the closure point to node "g" on the return side. The transmission coefficients calculated for the return side demonstrate that less than 10% of the pressure pulse propagates to the header. Because of the similar flow area changes, less than 10% of any pressure would propagate into the supply header upstream of point "a". In general, this indicates that the header acts like a large pressurized reservoir during the void closure process and water in the supply header does not add to the inertia of the decelerating water column.

Note: if desired, a plant could select a length all the way back to the pumps. However, this is considered excessively conservative.

The length if the accelerating water column is then:

$$Lwo := L_{ab} + L_{bc} \qquad Lwo = 176.2\,ft$$

Check: are the lengths within the bounds of the RBM runs?

Lao < 100 ft

Lwo < 400 ft ===>> yes lengths are within bounds of RBM runs

7.4.3 GAS RELEASE AND MASS OF AIR CONCENTRATED IN VOID

The mass of air concentrated in the void during the void phase of the transient is calculated by assuming that the water that has experienced boiling and subsequent condensation releases its air as described in Section 5 of the User's Manual.

For this problem, the tube volume only will be credited, assuming a draining of the FCU in which the headers do not remain full. This mass of water will release 50% of its non-condensable gas.

$V_{fcu} = 7.998\,ft^3$ or $V_{fcu} = 226\,liter$ from 7.4.2

This represents the mass of water in the tubes which will lose 50% of its non-condensable gas. The concentration of gas is obtained from Figure 5-3.

$$T_{des} = 95\,F$$

$$\frac{T_{des} - 32F}{1.8F} = 35 \quad \text{deg C}$$

$$CON_{air} := 18.5\,\frac{mg}{liter}$$ From Figure 5-3

$$m_{air} := 0.5 \cdot CON_{air} \cdot V_{fcu}$$

$$m_{air} = 2095\,mg$$

Check: is the mass of air within bounds of UM?

for void closure in 8" piping there should be at least 900 mg of air per Table 5.2

===> yes, mass if air is within RBM run bounds.

7.4.4 Cushioned VELOCITY

The graphs presented in Appendix A for the velocity ratios are solutions to the simultaneous differential equations that capture the acceleration of the advancing column and pressurization of the void.

In order to determine the cushioned velocity the following terms that are needed are repeated:

$$V_{initial} = 8.538 \frac{ft}{s}$$

$$K_{void} = 51$$

$$Lao = 106.622 \, ft$$

$$Lwo = 176.2 \, ft$$

$$m_{air} = 2.095 \times 10^3 \, mg$$

$$T_{void} = 217.1 \, F$$

Check: is the temperature within the bounds of the RBM?

Tvoid > 200 F ===> yes, the temperature is within the RBM run bounds

7.4.4.1 Air Cushioning

If only credit for air cushioning is considered then Figure A-13 from Appendix A is selected. This figure corresponds to 10" piping while the sample problem has 8" piping. 10" piping bounds the 8" piping since the inertia modeled in the 10" piping runs is greater than that in the 8" piping runs and the velocity has reached a steady state until the final void closure occurs. This is apparent by comparison of the 4" and 10" RBM run results for the same gas mass; the velocity is reduced more in the smaller pipe case. ***If the pipe size at a given plant is not shown then the Velocity Ratio chart for the next larger size pipe will always be bounding.***

Figure A-13 corresponds to an initial velocity of 10 fps. The initial velocity calculated in this sample problem is less. The higher velocity chart is selected because the higher momentum associated with the higher velocity bounds the lower velocity. ***If the initial velocity at a plant is not shown then the Velocity Ratio chart for the next larger velocity will always be bounding.***

For a K of 51 as calculated in the sample problem, from Figure A-10 the ratio of the second to initial velocity is:

$$\boxed{\frac{V_{cushion}}{V_{initial}} = 88\%}$$ only air cushion credited

Therefore, the final closure velocity will be reduced by 12% just considering air in this sample problem. Pressure "clipping" is not included here and is calculated later.

7.4.4.2 Air and Steam Cushioning

The velocity that results by considering steam cushioning is found using Figure A-40 from Appendix A. Note that the condensing surface temperature was verified being within the bounds of the RBM run limitations so steam condensation cushioning may be credited. The steam and air cushioning result in a ratio of cushioned to initial velocity of:

$$\boxed{\frac{V_{cushion}}{V_{initial}} = 83\%}$$ air and steam cushioning

The cushioned velocity is then:

$$\boxed{V_{cushion} := 0.83 \cdot V_{initial}} \qquad V_{cushion} = 7.1\,\frac{ft}{s}$$

7.4.5 SONIC VELOCITY

The sonic velocity is calculated from Equation 5-1 and 5-2 in the main body of the User's Manual.

$$P_{void} = 16.3\,psi$$

$$C = \sqrt{\frac{\frac{B}{\rho}}{\left(1 + \frac{B \cdot OD}{E \cdot t}\right)}}$$

where
B=bulk modulus of water $B := 319000psi$
E=Young's modulus for steel
OD=outside diameter of pipe $E := 28 \cdot 10^6 psi$
t=wall thickness

$$C := \sqrt{\frac{\frac{B}{\rho_{wtr}}}{\left[1 + \frac{B \cdot OD_{bcd}}{E \cdot \frac{\left(OD_{bcd} - ID_{bcd}\right)}{2}}\right]}} \qquad C = 4274\,\frac{ft}{s}$$

7.4.6 PEAK PRESSURE PULSE WITH NO "CLIPPING"

The peak waterhammer pressure is calculated using the Joukowski equation with a coefficient of 1/2 for a water on water closure:

$$\Delta P_{no\_clipping} := \frac{1}{2} \cdot \rho_{wtr} \cdot C \cdot V_{cushion}$$

$$\Delta P_{no\_clipping} = 203 \text{ psi}$$

7.4.7 RISE TIME

The rise time is calculated by using equation 5-4 from the UM.

$$ms := 0.001s$$

$$TR := 0.5sec \cdot \left(\frac{V_{cushion}}{\frac{ft}{sec}} \right)^{-1.3} \qquad TR = 39\,ms$$

7.4.8 TRANSMISSION COEFFICIENTS

The pressure pulse may be affected by rarefaction waves as it is developing and the peak may be "clipped". In addition, the pressure may be attenuated as it propagates through the system as a result of area changes. In order to calculate each of these effects, the transmission coefficients at junctions is required. The transmission coefficients are calculated consistent with section 5.3 of the UM.

At points "f" and "g" the transmission coefficients are calculated using Equation 5-8 from the UM; for simplification here the sonic velocity is assumed to be constant up and downstream of the junction:

$$\tau = \frac{2 \cdot A_{incident}}{A_{incident} + \sum_j A_j}$$

$$\tau_f := \frac{2 \cdot A_{bcd}}{A_{bcd} + A_{abf} + A_{abf}} \qquad \tau_f = 0.312$$

=> this fraction of the incident pulse continues past point "f" and the remainder of the incident pulse returns towards the initiation point.

$$\tau_g := \frac{2 \cdot A_{abf}}{A_{abf} + A_{ag} + A_{ag}} \qquad \tau_g = 0.288$$

=> this fraction pulse that is incident upon point "g" continues past point "g" and the remainder of the incident pulse returns towards the initiation point.

$$\tau_{total} := \tau_f \cdot \tau_g$$

$$\tau_{total} = 0.09$$

When the pressure pulse travels past point "g" only 10% of the pulse will continue on. 69% of the incident pulse was reflected as a negative pulse at point "f" and then 71% of the pulse that was incident upon point "g" was reflected back as a negative pulse. the net reflection effect is:

$$\boxed{P_{ref} = P_{inc} \cdot (-69\%) + (31\% \cdot P_{inc}) \cdot (-71\%) = P_{inc}(-69\% - 47\% \cdot 71\%) = 91\%}$$

This reflection travels back to the initiation point. The pulse at the initiation point is 9% of its original value when this reflection arrives. For simplicity, the compounding effect of the "f" node transmission coefficient on the reflected wave from node "g" is ignored.

The transmission coefficient evaluation needs to consider the control valve. The transmission coefficient at the control valve is calculated by assuming the valve acts like an orifice as the pressure pulse propagates through it. Equation 5-14 provides a simple relationship for an orifice flow coefficient in terms of its diameter ratio (β). This equation is used to back calculate an equivalent β ratio for the control valve knowing its coefficient and assuming Co=0.6.

$\beta := 0.5$ Initial guess for the iteration below

$$\beta := \mathrm{root}\left[\left(\frac{1}{0.6 \cdot \beta^2} - 1\right)^2 - K_{vlv}, \beta\right] \qquad \beta = 0.347$$

For this β ratio and for the approximate waterhammer pressure already solved, the control valve will have a slight effect on the pressure pulse propagation by inspection of Figure 5-15. The reflection from this interaction will add approximately 10% to the incident pulse.

In general what this means is that 10% of the pulse magnitude is reflected in a positive sense back towards the initiation point. To account for this effect, the peak pressure pulse is conservatively increased by 10%.

7.4.9 DURATION

The pressure pulse is reduced to approximately 10% of its peak value as a result of the reflections from the area changes at points "f" and "g". As a result, the time that it takes the pressure pulse to travel to point "g" and back may be used to calculate the pressure pulse duration.

$$TD_{eg} := \frac{(L_{de} + L_{ef} + L_{fg}) \cdot 2}{C} \qquad TD_{eg} = 118.2\,\text{ms}$$

Time for pulse to travel to and from point "g". Note that reflections from "a" and "b" are not credited.

The total duration is conservatively increased by adding the rise time.

$$TD := TD_{eg} + TR$$

$$TD = 157\,\text{ms}$$

7.4.10 PRESSURE CLIPPING

The peak pressure is checked for "clipping" using Table 5-3.

$$L_e := L_{de} + L_{ef} + L_{fg} \qquad L_e = 252.6\,\text{ft} \qquad TR \cdot \frac{C}{2} = 84\,\text{ft} \qquad \tau_{total} = 0.09$$

This corresponds to the conditions in row two of the table referenced and no pressure clipping is expected.

$$\boxed{\Delta P := 1.1 \cdot \Delta P_{no\_clipping}}$$

1.1 is from the control valve

$$\Delta P = 223\,\text{psi}$$

7.4.11 PRESSURE PULSE SHAPE

The pulse shape is then characterized by four points.

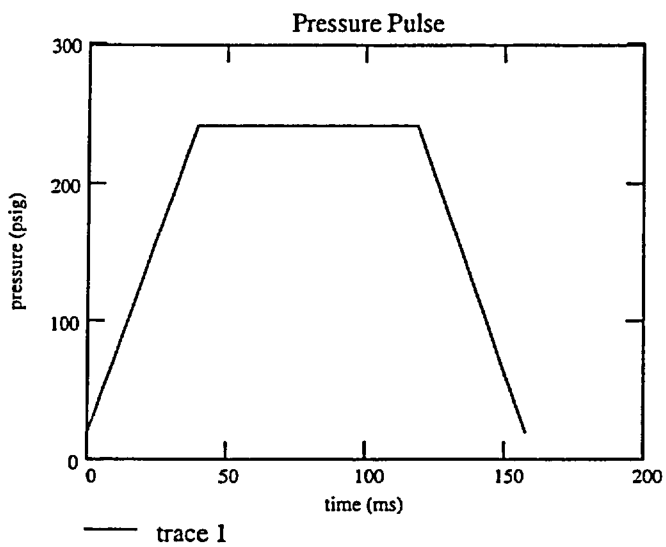
$\boxed{Psys := 19psi}$ this is the steady state system pressure [Ref. FAI/97-60 Rev. 2]

Using an index, i=0,1,2,3 $i := 0..3$

$time_i :=$	$pressure_i :=$
0ms	Psys
TR	ΔP + Psys
TD − TR	ΔP + Psys
TD	Psys

This provides the following values, which are plotted below.

$$time = \begin{pmatrix} 0 \\ 0.039 \\ 0.118 \\ 0.157 \end{pmatrix} s \qquad pressure = \begin{pmatrix} 19 \\ 242 \\ 242 \\ 19 \end{pmatrix} psi$$



Calculate the area underneath the curve to get the pressure impulse:

$$integral := TR \cdot \Delta P + \Delta P \cdot (TD_{eg} - TR)$$

$$integral = 1.817 \times 10^5 \frac{kg}{m\,s}$$

$impulse := integral \cdot A_{bcd}$ $\qquad impulse = 1.318 \times 10^3 lbf \cdot s$

7.4.12 FLOW AREA ATTENUATION

To simplify the analysis of the SW structures, the approach suggested here is to take the initiating pressure pulse and propagate the pulse through the system. For this example problem, the duration of the pulse is assumed to remain unchanged as it travels. In reality, the duration of the pulse is shortened as it approaches negative reflection sites. Maintaining the duration conservatively increases the impulse.

As the pressure pulse propagates through the system it will be atenuated/amplified by flow area changes. For this example, only the downstream propagation is considered. The pulse will be attenuated by the increase in area at "f" and "g". The transmission coefficients were previously calculated.

incident pulse	pulse transmission	transmitted pulse
$\Delta P = 223\,\text{psi}$	$\Delta P_f := \tau_f \cdot \Delta P$	$\Delta P_f = 70\,\text{psi}$
$\Delta P_f = 70\,\text{psi}$	$\Delta P_g := \tau_g \cdot \Delta P_f$	$\Delta P_g = 20\,\text{psi}$

Downstream of point "g" only the following pulse magnitude will remain: $\Delta P_g = 20\,\text{psi}$

APPENDIX D

Point Beach CFC 2D EPRI TBR Waterhammer Calculations Using MathCad 2000

POINT BEACH CFC 2D

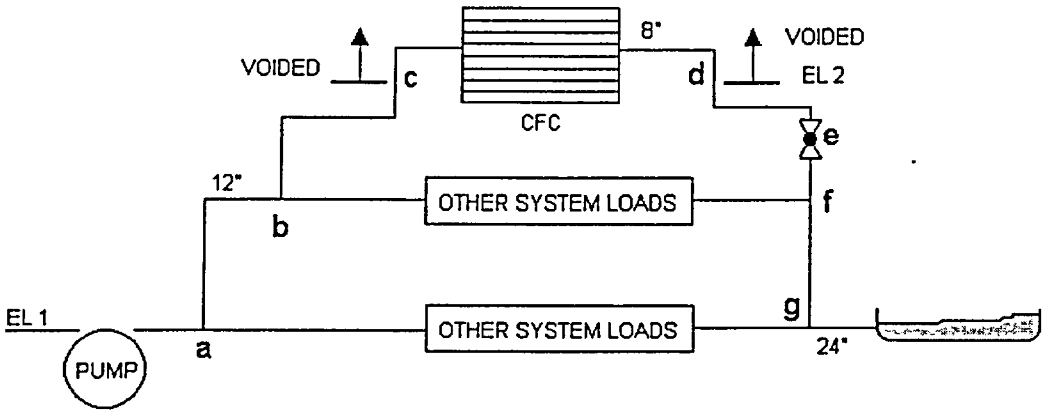


Figure 1 Open Loop Configuration

Pressure & Temperature

Note, pressures listed as "psi" are absolute (psia) or differential (psid) unless otherwise stated

$P_{atm} := 14.7 \cdot psi$	Pressure above reservoir and above heat sink (absolute)
$T_{void} := 204.4 \cdot F$	Temperature in the void when the pumps restart (i.e. surface temperature of piping) [Ref. FAI/97-60 Rev. 2] (Assumed average T in void at 26 sec)
$T_{pipe\_initial} := 75 \cdot F$	Temperature of the fluid and piping when the transient starts [Ref. FAI/97-60 Rev. 2]

Pipe Geometry

$EL_1 := 33.2 \cdot ft$	Elevation of node "1" [Ref. FAI/97-60 Rev. 2]
$EL_2 := 30.3 \cdot ft$	Elevation of node "2" [Ref. FAI/97-60 Rev. 2]
$L_{ab} := 36.8 \cdot ft$	Length from node "a" to node "b" [Ref. FAI/97-60 Rev. 2]
$L_{bc} := 161.8 \cdot ft$	Length from node "b" to node "c" [Ref. FAI/97-60 Rev. 2]
$L_{cd} := 46.5 \cdot ft$	Length from node "c" to node "d" [Ref. FAI/97-60 Rev. 2]
$L_{de} := 161.2 \cdot ft$	Length from node "d" to node "e" [Ref. FAI/97-60 Rev. 2]
$L_{ef} := 6.4 \cdot ft$	Length from node "e" to node "f" [Ref. FAI/97-60 Rev. 2]
$L_{fg} := 86.8 \cdot ft$	Length from node "f" to node "g" [Ref. FAI/97-60 Rev. 2]
$L_{g\_sink} := 400 \cdot ft$	Length from node "g" to the ultimate heat sink [Ref. N/A -not used]
$ID_{abf} := 13.124 \cdot in$	I.D. of piping along path from "a" to "b" to "f" [Ref. FAI/97-60 Rev. 2]
$ID_{bcd} := 7.981 \cdot in$	I.D. of piping along path from "b" to "c" to "d" [Ref. FAI/97-60 Rev. 2]
$ID_{ag} := 22.624 \cdot in$	I.D. of piping along remaining path from "a" to "g" [Ref. FAI/97-60 Rev. 2]
$OD_{bcd} := 8.625 \cdot in$	O.D. of piping along path from "b" to "c" to "d" [Ref. FAI/97-60 Rev. 2]

Flows

$Q_{abf} := 800 \frac{gal}{min}$ Flow along path from "a" to "b" to "f" during steady state condition without voiding [Ref. FAI/97-60 Rev. 2]

$Q_{bcd} := 941 \cdot \frac{gal}{min}$ Flow along path from "b" to "c" to "d" during steady state condition without voiding [Ref. FAI/97-60 Rev. 2]

$Q_{ag} := 5100 \frac{gal}{min}$ Flow along path from "a" to "g during steady state condition without voiding [Ref. Chuck Richardson Emails dated 1/27/03 & 1/28/03]

FCU Characteristics

$N_{tube} := 240$ Number of tubes in cooler [Ref. FAI/97-60 Rev. 2]

$ID_{tube} := 0.527 \cdot in$ Internal diameter of tubes [Ref. FAI/97-60 Rev. 2]

$L_{tube} := 22 \cdot ft$ Length of tubes [Ref. FAI/97-60 Rev. 2]

Pump Characteristics

$H_s := 240.8 \cdot ft$ Pump shutoff head [Ref. Chuck Richardson Emails dated 1/27/03 & 1/28/03]

$A1 := 0.2547 \cdot \frac{sec}{ft^2}$ 1st order pump curve coefficient [Ref. Chuck Richardson Emails dated 1/27/03 & 1/28/03]

$A2 := -0.5783 \cdot \frac{sec^2}{ft^5}$ 2nd order pump curve coefficient [Ref. Chuck Richardson Emails dated 1/27/03 & 1/28/03]

$Hpump(Qp) := A2 \cdot Qp^2 + A1 \cdot Qp + H_s$ Pump curve equation

Other Inputs

$K_{vlv} := 139.326$ Valve frictional flow coefficient for throttled globe valve [Ref. FAI/97-60 Rev. 2]

$V_{wtr\_fcu} := 0.0 \cdot ft^3$ Volume of water that is left in the FCU when the pump restarts [Ref. FAI/97-60 Rev. 2]

$V_{wtr\_2phase} := 6 \cdot ft^3$ Volume of water that flows into the cooler after voiding has started and before the pumps restart. This volume of water is exposed to two phase flow conditions. [Ref. N/A -not used]

$\rho_{wtr} := 62 \cdot \frac{lb}{ft^3}$ Water density

$T_{des} := 95 \cdot F$ Design temp of the system

$R_{gas} := 1717 \cdot \frac{ft^2}{sec^2 \cdot R}$ Gas constant

Pump Flow Rate Equation

$$Qtot_{normal} := Q_{ag} + Q_{bcd} + Q_{abf} \qquad H_{norm} := Hpump(Qtot_{normal})$$

$$Qtot_{normal} = 6.841 \times 10^3 \frac{gal}{min} \qquad H_{norm} = 110\,ft$$

The total system flow rate is solved at any pump operating point using:

$$Qpump(Hd) := \frac{-A1 - \sqrt{A1^2 - 4 \cdot A2 \cdot (H_s - Hd)}}{2 \cdot A2}$$

$$Qpump(H_{norm}) = 6.841 \times 10^3 \frac{gal}{min}$$

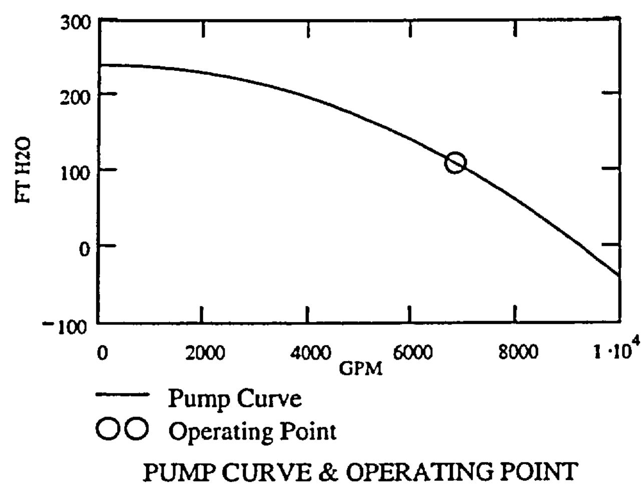


Figure 2 SW Pump Curve

7.4.1 Initial Velocity & FLOW COEFFICIENT PREDICTION

The water at the front of the void (point "d") is assumed to not move or simplification of this problem. More detailed hydraulic modeling may be performed to determine the reverse or forward flow at point "d". In many cases this flow is less than 10% of the incoming flow.

After combining parallel paths the system is then simplified to:

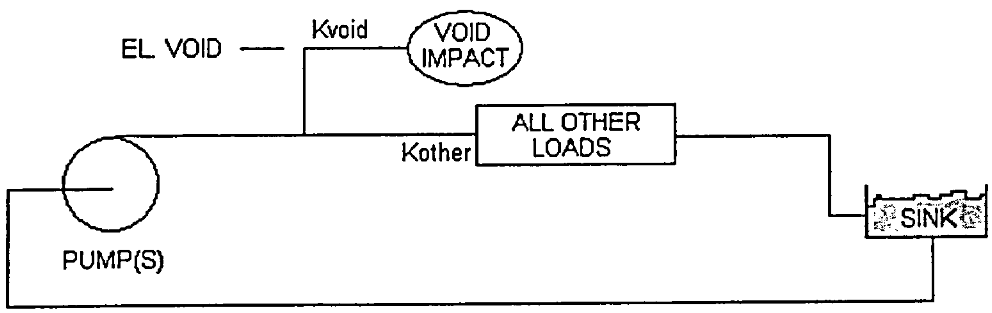


Figure 3 Simplified Open Loop Model

In terms of the initial flow diagram (Figure 1), the flow area for each path is calculated:

$$A_{abf} := \frac{\pi}{4}\cdot ID_{abf}^{2} \qquad A_{bcd} := \frac{\pi}{4}\cdot ID_{bcd}^{2} \qquad A_{ag} := \frac{\pi}{4}\cdot ID_{ag}^{2}$$

$$A_{abf} = 0.939\,ft^2 \qquad A_{bcd} = 0.347\,ft^2 \qquad A_{ag} = 2.792\,ft^2$$

The velocity for each path is calculated:

$$V_{abf} := \frac{Q_{abf}}{A_{abf}} \qquad V_{bcd} := \frac{Q_{bcd}}{A_{bcd}} \qquad V_{ag} := \frac{Q_{ag}}{A_{ag}}$$

$$V_{abf} = 1.9\,\frac{ft}{s} \qquad V_{bcd} = 6\,\frac{ft}{s} \qquad V_{ag} = 4.1\,\frac{ft}{s}$$

Calculate equivalent velocity for all other loads:

$$V_{eq} := \frac{Q_{abf} + Q_{ag}}{A_{abf} + A_{ag}}$$

$$V_{eq} = 3.523\,\frac{ft}{s}$$

The flow coefficient for each path is calculated.

The flow resistance from point "a" to point "b" and from point "f" to point "g" are assumed to have a negligible effect on the flow split to the different paths. *In an actual plant system, the engineer may choose to use values from a previously qualified system hydraulic model to determine a more accurate initial velocity.*

$$h_f = K \cdot \frac{V^2}{2 \cdot g} \quad => \quad K = \frac{2 \cdot g \cdot h_f}{V^2}$$

$$K_{abf} := \frac{2 \cdot g \cdot H_{norm}}{V_{abf}^{\,2}} \qquad K_{bcd} := \frac{2 \cdot g \cdot H_{norm}}{V_{bcd}^{\,2}} \qquad K_{ag} := \frac{2 \cdot g \cdot H_{norm}}{V_{ag}^{\,2}}$$

$$K_{abf} = 1.972 \times 10^3 \qquad K_{bcd} = 195 \qquad K_{ag} = 429$$

An equivalent flow coefficient for the "other loads" path (Figure 1) is calculated from:

$$K_{other} := \left(\frac{A_{abf}}{\frac{A_{abf}}{\sqrt{K_{abf}}} + \frac{A_{ag}}{\sqrt{K_{ag}}}} \right)^2 \qquad K_{other} = 36 \qquad A_{other} := A_{abf} \qquad ID_{other} := ID_{abf}$$

An equivalent flow coefficient from all other loads is calculated from:

$$K_{other} := \frac{2 \cdot g \cdot H_{norm}}{V_{eq}^{\,2}} \qquad A_{other} := A_{abf} + A_{ag}$$

$$K_{other} = 571.989 \qquad ID_{other} := \left(\frac{4 \cdot A_{other}}{\pi} \right)^{0.5} \qquad ID_{other} = 2.18\,\text{ft}$$

The flow coefficient for the path to the void is calculated by subtracting the flow coefficient downstream of the void along this path. To simplify this sample problem only the valve resistance downstream of the void is considered:

$$K_{void} := K_{bcd} - K_{vlv} \qquad K_{void} = 56$$

The pressure in the void is assumed to correspond to the saturation pressure for the void temperature.

$P_{void} := 12.7 \cdot \text{psi}$ Absolute pressure based on saturation pressure of Tvoid shown above.
Comes from TREMOLO output. [Ref. FAI/97-60, Rev. 2]

The pump total developed head (TDH) is written by using Bernoulli's equation:

$H_{atm} + EL_1 + TDH = H_{void} + EL_2 + H_f$ where the following terms are defined in terms of feet H2O

H_{atm} = atmospheric pressure head

EL_1 = elevation of node "1"

TDH = total developed head from pump

EL_2 = elevation of node "2"

H_f = frictional losses from point "1" to "2"

The frictional losses are written using Darcy's formula with an appropriate units conversion factor:

$$H_f = 0.00259 \cdot K_{loss} \cdot \frac{Q^2}{ID^4}$$

where

K_{loss} = loss coefficient

Q = flow rate in gpm

ID = pipe diameter in inches

Two equations for the total developed head (TDH) by the pump are written with a corresponding flow balance and initial guesses for the simultaneous solution of these equations:

$Q_{void} := .1 \qquad Q_{other} := .5 \qquad TDH := 300$

Given

$$TDH = 0.00259 \cdot K_{other} \cdot \frac{Q_{other}^{\ 2}}{\left(\frac{ID_{other}}{in}\right)^4}$$

frictional losses along "other" path equal the total developed head

$$TDH = 0.00259 \cdot K_{void} \cdot \frac{Q_{void}^{\ 2}}{\left(\frac{ID_{bcd}}{in}\right)^4} + \left(EL_2 - EL_1 - \frac{P_{atm}}{\rho_{wtr} \cdot g} + \frac{P_{void}}{\rho_{wtr} \cdot g}\right) ft^{-1}$$

Bernoulli's along the "void" path

$$Q_{other} + Q_{void} = Qpump(TDH \cdot ft) \left(\frac{gal}{min}\right)^{-1}$$

pump curve

The solution to the simultaneous equations is solved and defined as "Results".

$Results := Find(TDH, Q_{other}, Q_{void})$

$TDH := Results_0 \cdot ft \qquad TDH = 95.792\,ft$

$Q_{other} := Results_1 \cdot \frac{gal}{min} \qquad Q_{other} = 5.501 \times 10^3 \frac{gal}{min}$

$Q_{void} := Results_2 \cdot \frac{gal}{min} \qquad Q_{void} = 1.706 \times 10^3 \frac{gal}{min}$

The initial velocity is then:

$V_{initial} := \frac{Q_{void}}{A_{bcd}} \qquad V_{initial} = 10.9 \frac{ft}{s}$

The total resistance for this path is:

$K_{void} = 56$

Check: is the velocity within the RBM bounds?

$V_{initial}$ < 20 ft/sec ===> yes, velocity is within bounds of RBM runs

7.4.2 VOID & WATER COLUMN LENGTHS

The volume of piping that is voided is calculated:

$$V_{pipe\_voided} := L_{cd} \cdot \frac{\pi}{4} \cdot ID_{bcd}^{\ 2} \qquad V_{pipe\_voided} = 16\,ft^3$$

The void of the fan cooler unit is calculated.

$$V_{fcu} := N_{tube} \cdot L_{tube} \cdot \frac{\pi}{4} \cdot ID_{tube}^{\ 2} \qquad V_{fcu} = 8\,ft^3$$

The equivalent void length is then:

$$Lao := \frac{V_{pipe\_voided} + V_{fcu}}{A_{bcd}} \qquad Lao = 70\,ft$$

The initial water column length is assumed to be the distance from point "a" to point "c". The discussion that follows explains why point "a" was chosen.

Ignoring the FCU, the flow area changes from the closure point to node "a" are the same as the area changes from the closure point to node "g" on the return side. The transmission coefficients calculated for the return side demonstrate that less than 10% of the pressure pulse propagates to the header. Because of the similar flow area changes, less than 10% of any pressure would propagate into the supply header upstream of point "a". In general, this indicates that the header acts like a large pressurized reservoir during the void closure process and water in the supply header does not add to the inertia of the decelerating water column.

Note: if desired, a plant could select a length all the way back to the pumps. However, this is considered excessively conservative.

The length if the accelerating water column is then:

$$Lwo := L_{ab} + L_{bc} \qquad Lwo = 198.6\,ft$$

Check: are the lengths within the bounds of the RBM runs?

Lao < 100 ft

Lwo < 400 ft ===>> yes lengths are within bounds of RBM runs

7.4.3 GAS RELEASE AND MASS OF AIR CONCENTRATED IN VOID

The mass of air concentrated in the void during the void phase of the transient is calculated by assuming that the water that has experienced boiling and subsequent condensation releases its air as described in Section 5 of the User's Manual.

For this problem, the tube volume only will be credited, assuming a draining of the FCU in which the headers do not remain full. This mass of water will release 50% of its non-condensable gas.

$V_{fcu} = 7.998\,ft^3$ or $V_{fcu} = 226\,liter$ from 7.4.2

This represents the mass of water in the tubes which will lose 50% of its non-condensable gas. The concentration of gas is obtained from Figure 5-3.

$$T_{des} = 95\,F$$

$$\frac{T_{des} - 32F}{1.8F} = 35 \quad \text{deg C}$$

$$CON_{air} := 18.5\,\frac{mg}{liter} \qquad \text{From Figure 5-3}$$

$$m_{air} := 0.5 \cdot CON_{air} \cdot V_{fcu}$$

$$m_{air} = 2095\,mg$$

Check: is the mass of air within bounds of UM?

for void closure in 8" piping there should be at least 900 mg of air per Table 5.2

===> yes, mass if air is within RBM run bounds.

7.4.4 Cushioned VELOCITY

The graphs presented in Appendix A for the velocity ratios are solutions to the simultaneous differential equations that capture the acceleration of the advancing column and pressurization of the void.

In order to determine the cushioned velocity the following terms that are needed are repeated:

$$V_{initial} = 10.941 \frac{ft}{s}$$

$$K_{void} = 56$$

$$Lao = 69.522\,ft$$

$$Lwo = 198.6\,ft$$

$$m_{air} = 2.095 \times 10^3\,mg$$

$$T_{void} = 204.4\,F$$

Check: is the temperature within the bounds of the RBM?

Tvoid > 200 F ===> yes, the temperature is within the RBM run bounds

7.4.4.1 Air Cushioning

If only credit for air cushioning is considered then Figure A-13 from Appendix A is selected. This figure corresponds to 10" piping while the sample problem has 8" piping. 10" piping bounds the 8" piping since the inertia modeled in the 10" piping runs is greater than that in the 8" piping runs and the velocity has reached a steady state until the final void closure occurs. This is apparent by comparison of the 4" and 10" RBM run results for the same gas mass; the velocity is reduced more in the smaller pipe case. ***If the pipe size at a given plant is not shown then the Velocity Ratio chart for the next larger size pipe will always be bounding***

Figure A-13 corresponds to an initial velocity of 10 fps. The initial velocity calculated in this sample problem is less. The higher velocity chart is selected because the higher momentum associated with the higher velocity bounds the lower velocity. ***If the initial velocity at a plant is not shown then the Velocity Ratio chart for the next larger velocity will always be bounding.***

For a K of 56 as calculated in the sample problem, from Figure A-13 the ratio of the second to initial velocity is:

$$\boxed{\frac{V_{cushion}}{V_{initial}} = 87\%}$$ only air cushion credited

Therefore, the final closure velocity will be reduced by 13% just considering air in this sample problem. Pressure "clipping" is not included here and is calculated later.

7.4.4.2 Air and Steam Cushioning

The velocity that results by considering steam cushioning is found using Figure A-40 from Appendix A. Note that the condensing surface temperature was verified being within the bounds of the RBM run limitations so steam condensation cushioning may be credited. The steam and air cushioning result in a ratio of cushioned to initial velocity of:

$$\boxed{\frac{V_{cushion}}{V_{initial}} = 83\%}$$

air and steam cushioning

The cushioned velocity is then:

$$\boxed{V_{cushion} := 0.83 \cdot V_{initial}} \qquad V_{cushion} = 9.1\frac{ft}{s}$$

7.4.5 SONIC VELOCITY

The sonic velocity is calculated from Equation 5-1 and 5-2 in the main body of the User's Manual.

$$P_{void} = 12.7\,psi$$

where
B=bulk modulus of water $B := 319000psi$
E=Young's modulus for steel
OD=outside diameter of pipe $E := 28 \cdot 10^{6} psi$
t=wall thickness

$$C = \sqrt{\frac{\frac{B}{\rho}}{\left(1 + \frac{B \cdot OD}{E \cdot t}\right)}}$$

$$C := \sqrt{\frac{\frac{B}{\rho_{wtr}}}{\left[1 + \frac{B \cdot OD_{bcd}}{E \cdot \frac{(OD_{bcd} - ID_{bcd})}{2}}\right]}} \qquad C = 4274\frac{ft}{s}$$

7.4.6 PEAK PRESSURE PULSE WITH NO "CLIPPING"

The peak waterhammer pressure is calculated using the Joukowski equation with a coefficient of 1/2 for a water on water closure:

$$\Delta P_{no\_clipping} := \frac{1}{2} \cdot \rho_{wtr} \cdot C \cdot V_{cushion}$$

$$\Delta P_{no\_clipping} = 260\,\text{psi}$$

7.4.7 RISE TIME

The rise time is calculated by using equation 5-4 from the UM.

$$ms := 0.001s$$

$$TR := 0.5sec \cdot \left(\frac{V_{cushion}}{\frac{ft}{sec}} \right)^{-1.3} \qquad TR = 28\,ms$$

7.4.8 TRANSMISSION COEFFICIENTS

The pressure pulse may be affected by rarefaction waves as it is developing and the peak may be "clipped". In addition, the pressure may be attenuated as it propagates through the system as a result of area changes. In order to calculate each of these effects, the transmission coefficients at junctions is required. The transmission coefficients are calculated consistent with section 5.3 of the UM.

At points "f" and "g" the transmission coefficients are calculated using Equation 5-8 from the UM; for simplification here the sonic velocity is assumed to be constant up and downstream of the junction:

$$\tau = \frac{2 \cdot A_{incident}}{A_{incident} + \sum_j A_j}$$

$$\tau_f := \frac{2 \cdot A_{bcd}}{A_{bcd} + A_{abf} + A_{abf}} \qquad \tau_f = 0.312$$

=> this fraction of the incident pulse continues past point "f" and the remainder of the incident pulse returns towards the initiation point.

$$\tau_g := \frac{2 \cdot A_{abf}}{A_{abf} + A_{ag} + A_{ag}} \qquad \tau_g = 0.288$$

=> this fraction pulse that is incident upon point "g" continues past point "g" and the remainder of the incident pulse returns towards the initiation point.

$$\tau_{total} := \tau_f \cdot \tau_g$$

$$\tau_{total} = 0.09$$

When the pressure pulse travels past point "g" only 10% of the pulse will continue on. 69% of the incident pulse was reflected as a negative pulse at point "f" and then 71% of the pulse that was incident upon point "g" was reflected back as a negative pulse. the net reflection effect is:

$$\boxed{P_{ref} = P_{inc} \cdot (-69\%) + (31\% \cdot P_{inc}) \cdot (-71\%) = P_{inc}(-69\% - 47\% \cdot 71\%) = 91\%}$$

This reflection travels back to the initiation point. The pulse at the initiation point is 9% of its original value when this reflection arrives. For simplicity, the compounding effect of the "f" node transmission coefficient on the reflected wave from node "g" is ignored.

The transmission coefficient evaluation needs to consider the control valve. The transmission coefficient at the control valve is calculated by assuming the valve acts like an orifice as the pressure pulse propagates through it. Equation 5-14 provides a simple relationship for an orifice flow coefficient in terms of its diameter ratio (β). This equation is used to back calculate an equivalent β ratio for the control valve knowing its coefficient and assuming Co=0.6.

$\beta := 0.5$ Initial guess for the iteration below

$$\beta := \mathrm{root}\left[\left(\frac{1}{0.6 \cdot \beta^2} - 1\right)^2 - K_{vlv}, \beta\right] \qquad \beta = 0.361$$

For this β ratio and for the approximate waterhammer pressure already solved, the control valve will have a slight effect on the pressure pulse propagation by inspection of Figure 5-15. The reflection from this interaction will add approximately 10% to the incident pulse.

In general what this means is that 10% of the pulse magnitude is reflected in a positive sense back towards the initiation point. To account for this effect, the peak pressure pulse is conservatively increased by 10%.

7.4.9 DURATION

The pressure pulse is reduced to approximately 10% of its peak value as a result of the reflections from the area changes at points "f" and "g". As a result, the time that it takes the pressure pulse to travel to point "g" and back may be used to calculate the pressure pulse duration.

$$TD_{eg} := \frac{(L_{de} + L_{ef} + L_{fg}) \cdot 2}{C} \qquad TD_{eg} = 119.1\ \mathrm{ms}$$

Time for pulse to travel to and from point "g". Note that reflections from "a" and "b" are not credited.

The total duration is conservatively increased by adding the rise time.

$$TD := TD_{eg} + TR$$

$$TD = 147\ \mathrm{ms}$$

7.4.10 PRESSURE CLIPPING

The peak pressure is checked for "clipping" using Table 5-3.

$$L_e := L_{de} + L_{ef} + L_{fg} \qquad L_e = 254.4\ \mathrm{ft} \qquad TR \cdot \frac{C}{2} = 61\ \mathrm{ft} \qquad \tau_{total} = 0.09$$

This corresponds to the conditions in row two of the table referenced and no pressure clipping is expected.

$$\boxed{\Delta P := 1.1 \cdot \Delta P_{no\_clipping}}$$

1.1 is from the control valve

$$\Delta P = 286\ \mathrm{psi}$$

7.4.11 PRESSURE PULSE SHAPE

The pulse shape is then characterized by four points.

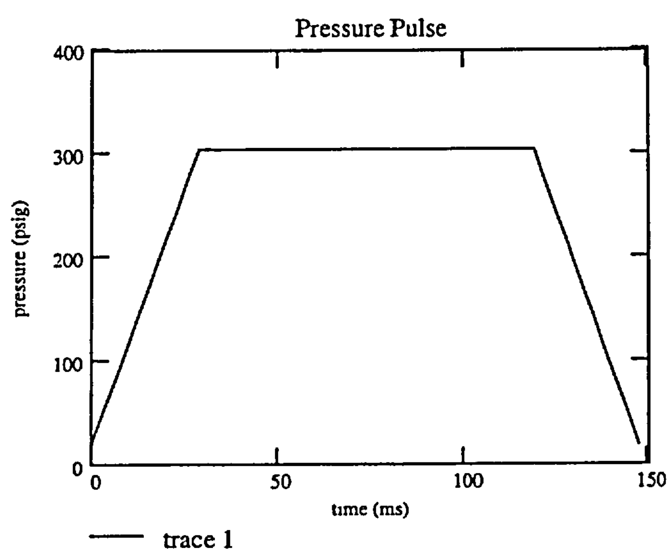
$\boxed{Psys := 19psi}$ this is the steady state system pressure [Ref. FAI/97-60 Rev. 2]

Using an index, i=0,1,2,3 $i := 0..3$

$time_i :=$	$pressure_i :=$
0ms	Psys
TR	ΔP + Psys
TD − TR	ΔP + Psys
TD	Psys

This provides the following values, which are plotted below.

$$time = \begin{pmatrix} 0 \\ 0.028 \\ 0.119 \\ 0.147 \end{pmatrix} s \qquad pressure = \begin{pmatrix} 19 \\ 305 \\ 305 \\ 19 \end{pmatrix} psi$$



Calculate the area underneath the curve to get the pressure impulse:

$$integral := TR \cdot \Delta P + \Delta P \cdot \left(TD_{eg} - TR\right)$$

$$integral = 2.345 \times 10^5 \frac{kg}{m\,s}$$

$$impulse := integral \cdot A_{bcd} \qquad impulse = 1.701 \times 10^3 \, lbf \cdot s$$

7.4.12 FLOW AREA ATTENUATION

To simplify the analysis of the SW structures, the approach suggested here is to take the initiating pressure pulse and propagate the pulse through the system. For this example problem, the duration of the pulse is assumed to remain unchanged as it travels. In reality, the duration of the pulse is shortened as it approaches negative reflection sites. Maintaining the duration conservatively increases the impulse.

As the pressure pulse propagates through the system it will be atenuated/amplified by flow area changes. For this example, only the downstream propagation is considered. The pulse will be attenuated by the increase in area at "f" and "g". The transmission coefficients were previously calculated.

incident pulse	pulse transmission	transmitted pulse
$\Delta P = 286\,\text{psi}$	$\Delta P_f := \tau_f \cdot \Delta P$	$\Delta P_f = 89\,\text{psi}$
$\Delta P_f = 89\,\text{psi}$	$\Delta P_g := \tau_g \cdot \Delta P_f$	$\Delta P_g = 26\,\text{psi}$

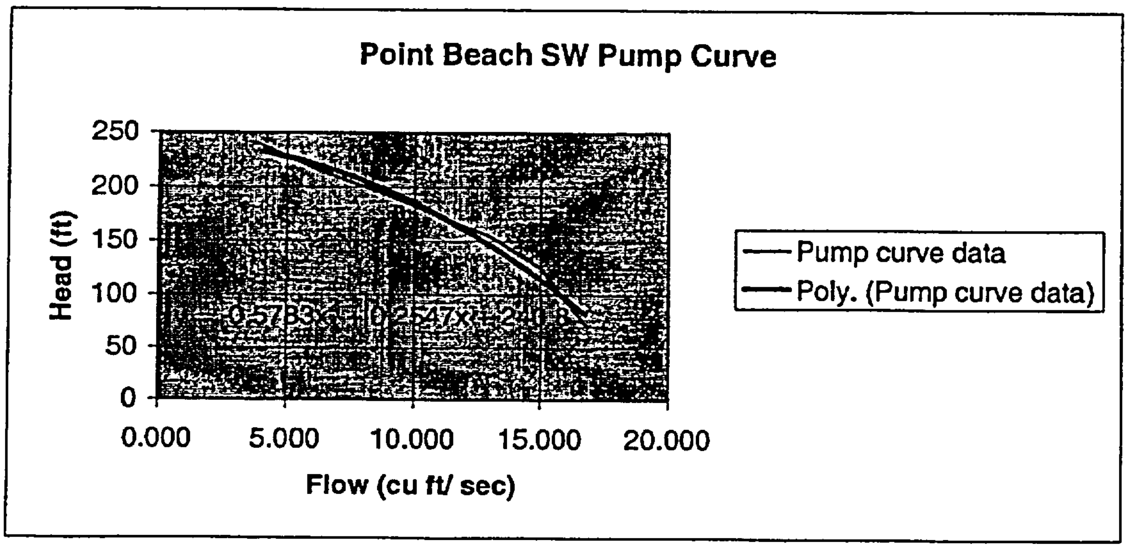
Downstream of point "g" only the following pulse magnitude will remain: $\Delta P_g = 26\,\text{psi}$

APPENDIX E

SERVICE WATER PUMP CURVE CALCULATIONS USING MICROSOFT EXCEL 97

Below is the pump-head curve for the Unit 1 & 2 Service Water Pump Curves for the Point Beach Waterhammer EPRI TBR Analysis. This curve was generated from the Unit 1 & 2 WATER data sent to FAI from Chuck Richardson (WEPCo) on January 27, 2002 (Unit 1) and January 28, 2002 (Unit 2). Therefore, from the data below using the EXCEL, the pump curve coefficients can be calculated using a polynomonial (A_2*Q^2 + A_1*Q + H) curve-fit features within EXCEL. As shown below, the coefficients are A_2 = -0.5783 and A_1 = 0.2547.

Flow (gpm)	Head (ft)	Flow (cu ft/s)
1814.05	237.95	4.042
2824.87	214.81	6.294
3823.52	196.22	8.519
4500	182.09	10.027
4739.93	177.08	10.561
5795.15	155.69	12.913
6735.92	125.45	15.009
7532.61	71.99	16.784



APPENDIX F

EPRI TBR MAX FORCE/IMPULSE CALCULATIONS FOR POINT BEACH CFC 1A USING MICROSOFT EXCEL 97

POINT BEACH CFC1A INPUTS:

Wave Speed (C) =	4274	ft/s			
Rise Time =	0.048	sec			
Duration =	0.127	sec			
Peak Pressure =	191	psia	Rate =	3979.166667	psi/sec
Area (8" line)	50	sq in			
Area (6" line)	28.89	sq in			
Area (2.5" line)	4.79	sq in			
Trans. Coeff. (elbows) =	1				
Trans. Coeff. (8" x 6") =	0.7759				
Trans. Coeff. (6" x 2 5") =	0.9234				

Direction - Downstream Towards Throttle Valve

Flow Element	Pipe Area (sq in)	Length (ft)	P1 -time	P2 -time	P3 -time	P4 - time	P5 -time
35	50	3.16	0	0.00074	0.04874	0 07974	0.12774
36	50	18	0	0.00495	0.05295	0 08395	0.13195
37	50	3	0	0.00565	0.05365	0.08465	0.13265
38	50	7	0	0 00729	0 05529	0 08629	0.13429
39	50	12	0	0 01010	0.05810	0 08910	0.13710
40	50	22.5	0	0.01536	0 06336	0.09436	0.14236
41	50	2	0	0.01583	0.06383	0.09483	0.14283
42	50	2	0	0.01630	0.06430	0.09530	0.14330
43	50	13	0	0.01934	0.06734	0.09834	0.14634

Direction - Upstream Towards Fan Cooler

Flow Element	Pipe Area (sq in)	Length (ft)	P1 -time	P2 -time	P3 -time	P4 -time	P5 -time
34(*)	50	14 83	0	0 00347	0 05147	0 08247	0.13047
33	50	6.5	0	0.00499	0.05299	0.08399	0.13199
32	50	4	0	0.00593	0.05393	0.08493	0.13293
31	50	6.4167	0	0.00743	0.05543	0.08643	0.13443
30	28.89	4.1	0	0.00839	0.05639	0.08739	0.13539
29	28.89	1.5	0	0.00874	0.05674	0.08774	0.13574
28	28.89	7.667	0	0.01053	0 05853	0.08953	0.13753
27	28.89	2.25	0	0 01106	0.05906	0 09006	0.13806
26	28.89	2.25	0	0.01158	0.05958	0 09058	0.13858

Direction - Downstream Towards Throttle Valve

Flow Element	Delta-Time (s)	Force (lbf)	Impulse (lbf-s)
35	0.00074	147.100686	7.060832943
36(*)	0.00421	592.495592	28.43978842
37(*)	0.00070	98.7492653	4.739964736
38	0 00164	325.855951	15.64108563

39	0.00281	558 610201	26.81328966
40(#)	0 00526	907.069922	43.53935626
41	0.00047	93.1017002	4.46888161
42(*)	0 00047	65.8328436	3.159976491
43	0.00304	605.161051	29.04773046

Direction - Upstream Towards Fan Cooler

Flow Elem	Delta-T (s)	Force (lbf)	Impulse (lbf-s)
34(*)	0 00347	488.150535	23.43122568
33	0.00152	302.580526	14.52386523
32	0.00094	186 2034	8.937763219
31(!)	0.00150	231.750205	11.12400986
30	0.00096	85.5598052	4.106870648
29	0.00035	31.3023677	1.502513652
28(!)	0 00179	147.748396	7.091923028
27(!)	0.00053	43.3590573	2 081234748
26(!)	0.00053	43.3590573	2.081234748

Notes:
(*) - denotes the flow element as a 45-degree elbow
(#) - denotes the flow element as a 30-degree elbow
(!) - denotes the flow element as a reducing tee

POINT BEACH CFC1A INPUTS:

Wave Speed (C) =	4274	ft/s			
Rise Time =	0 048	sec			
Duration =	0 127	sec			
Peak Pressure =	191	psia	Rate =	=C6/C4	psi/sec
Area (8" line)	50	sq in			
Area (6" line)	28 89	sq in			
Area (2 5" line)	4 79	sq in			
Trans. Coeff. (elbows) =	1				
Trans. Coeff (8" x 6") =	=2*C7/(C7+C7+C8)				
Trans. Coeff. (6" x 2 5") =	=2*C8/(C8+C8+C9)				

Direction - Downstream Towards Thrc

Flow Element	Pipe Area (sq in)	Length (ft)	P1 -time	P2 -time	P3 -time	P4 - time	P5 -time
35	50	3 16	0	=C17/C3	=E17+C4	=E17+(C5-C4)	=E17+C5
36	50	18	0	=(C17+C18)/C3	=E18+C4	=E18+(C5-C4)	=E18+C5
37	50	3	0	=(C17+C18+C19)/C3	=E19+C4	=E19+(C5-C4)	=E19+C5
38	50	7	0	=(C17+C18+C19+C20)/C3	=E20+C4	=E20+(C5-C4)	=E20+C5
39	50	12	0	=(C17+C18+C19+C20+C21)/C3	=E21+C4	=E21+(C5-C4)	=E21+C5
40	50	22 5	0	=(C17+C18+C19+C20+C21+C22)/C3	=E22+C4	=E22+(C5-C4)	=E22+C5
41	50	2	0	=(C17+C18+C19+C20+C21+C22+C23)/C3	=E23+C4	=E23+(C5-C4)	=E23+C5
42	50	2	0	=(C17+C18+C19+C20+C21+C22+C23+C24)/C3	=E24+C4	=E24+(C5-C4)	=E24+C5
43	50	13	0	=(C17+C18+C19+C20+C21+C22+C23+C24+C25)/C3	=E25+C4	=E25+(C5-C4)	=E25+C5

Direction - Upstream Towards Fan Co

Flow Element	Pipe Area (sq in)	Length (ft)	P1 -time	P2 -time	P3 -time	P4 -time	P5 -time
34(*)	50	14 83	0	=C30/C3	=E30+C4	=E30+(C5-C4)	=E30+C5
33	50	6 5	0	=(C30+C31)/C3	=E31+C4	=E31+(C5-C4)	=E31+C5
32	50	4	0	=(C30+C31+C32)/C3	=E32+C4	=E32+(C5-C4)	=E32+C5
31	50	6 4167	0	=(C30+C31+C32+C33)/C3	=E33+C4	=E33+(C5-C4)	=E33+C5
30	=C8	4.1	0	=(C30+C31+C32+C33+C34)/C3	=E34+C4	=E34+(C5-C4)	=E34+C5
29	=C8	1.5	0	=(C30+C31+C32+C33+C34+C35)/C3	=E35+C4	=E35+(C5-C4)	=E35+C5
28	=C8	7 667	0	=(C30+C31+C32+C33+C34+C35+C36)/C3	=E36+C4	=E36+(C5-C4)	=E36+C5
27	=C8	2 25	0	=(C30+C31+C32+C33+C34+C35+C36+C37)/C3	=E37+C4	=E37+(C5-C4)	=E37+C5
26	=C8	2 25	0	=(C30+C31+C32+C33+C34+C35+C36+C37+C38)/C3	=E38+C4	=E38+(C5-C4)	=E38+C5

Direction - Downstream Towards Thrc

Flow Element	Delta-Time (s)	Force (lbf)	Impulse (lbf-s)
35	=E17	=B43*F6*B17	=C43*C4
36(*)	=E18-E17	=B44*F6*B18*COS(45*PI()/180)	=C44*C4
37(*)	=E19-E18	=B45*F6*B19*COS(45*PI()/180)	=C45*C4
38	=E20-E19	=B46*F6*B20	=C46*C4

39	=E21-E20	=B47*F6*B21	=C47*C4
40(#)	=E22-E21	=B48*F6*B22*COS(30*PI()/180)	=C48*C4
41	=E23-E22	=B49*F6*B23	=C49*C4
42(*)	=E24-E23	=B50*F6*B24*COS(45*PI()/180)	=C50*C4
43	=E25-E24	=B51*F6*B25	=C51*C4

Direction - Upstream Towards Fan Co

Flow Elem	Delta-T (s)	Force (lbf)	Impulse (lbf-s)
34(*)	=E30	=B55*F6*B30*COS(45*PI()/180)	=C55*C4
33	=E31-E30	=B56*F6*B31	=C56*C4
32	=E32-E31	=B57*F6*B32	=C57*C4
31(!)	=E33-E32	=F6*B58*B33*C11	=C58*C4
30	=E34-E33	=B59*F6*B34*C11	=C59*C4
29	=E35-E34	=B60*F6*B35*C11	=C60*C4
28(!)	=E36-E35	=B61*F6*B36*C11*C12	=C61*C4
27(!)	=E37-E36	=B62*F6*B37*C11*C12	=C62*C4
26(!)	=E38-E37	=B63*F6*B38*C11*C12	=C63*C4

Notes:

(*) - denotes the flow element as a 45-de

(#) - denotes the flow element as a 30-de

(!) - denotes the flow element as a reduc

APPENDIX G

EPRI TBR MAX FORCE/IMPULSE CALCULATIONS FOR POINT BEACH CFC 1C USING MICROSFOT EXCEL 97

POINT BEACH CFC1C INPUTS:

Wave Speed (C) =	4274	ft/s			
Rise Time =	0.039	sec			
Duration =	0.118	sec			
Peak Pressure =	222	psia	Rate =	5692.307692	psi/sec
Area (8" line)	50	sq in			
Area (6" line)	28.89	sq in			
Area (2.5" line)	4.79	sq in			
Trans. Coeff. (elbows) =	1				
Trans. Coeff. (8" x 6") =	0.7759				
Trans. Coeff. (6" x 2.5") =	0.9234				

Direction - Downstream Towards Throttle Valve

Flow Element	Pipe Area (sq in)	Length (ft)	P1 -time	P2 -time	P3 -time	P4 - time	P5 -time
42	50	0.65	0	0.00015	0.03915	0.07915	0.11815
43	50	8.035	0	0.00203	0.04103	0.08103	0.12003
44	50	5.3	0	0.00327	0.04227	0.08227	0.12127
45	50	11	0	0.00585	0.04485	0.08485	0.12385
46	50	11	0	0.00842	0.04742	0.08742	0.12642
47	50	22	0	0.01357	0.05257	0.09257	0.13157
48	50	11	0	0.01614	0.05514	0.09514	0.13414
49	50	15	0	0.01965	0.05865	0.09865	0.13765
50	50	4	0	0 02059	0.05959	0.09959	0.13859
51	50	3	0	0.02129	0.06029	0.10029	0.13929

Direction - Upstream Towards Fan Cooler

Flow Element	Pipe Area (sq in)	Length (ft)	P1 -time	P2 -time	P3 -time	P4 -time	P5 -time
41	50	8.711	0	0.00204	0.04104	0.08104	0.12004
40	50	1.654	0	0.00243	0.04143	0.08143	0.12043
39	50	1.689	0	0.00282	0.04182	0.08182	0.12082
38	50	0.583	0	0.00296	0.04196	0.08196	0.12096
37	28.89	1.612	0	0.00333	0.04233	0.08233	0.12133
36	28.89	3.73	0	0.00421	0.04321	0.08321	0.12221
35	28.89	0.583	0	0.00434	0.04334	0.08334	0.12234
34	28.89	1.579	0	0.00471	0.04371	0.08371	0.12271
33	28.89	5.521	0	0.00600	0.04500	0.08500	0.12400
32	28.89	4.625	0	0.00709	0.04609	0.08609	0.12509
31	28.89	2.25	0	0.00761	0.04661	0.08661	0.12561
30	28.89	2.25	0	0.00814	0.04714	0.08714	0.12614

Direction - Downstream Towards Throttle Valve

Flow Element	Delta-Time (s)	Force (lbf)	Impulse (lbf-s)
42	0.00015	43.2849789	1.688114179
43	0.00188	535.068932	20.86768835
44	0.00124	352.939059	13.7646233
45	0.00257	732.515028	28.5680861
46(^)	0.00257	732.515028	28.5680861
47(@)	0.00515	1200.08237	46.80321226
48	0.00257	732.515028	28.5680861
49(*)	0.00351	706.317742	27.54639192
50(*)	0.00094	188.351398	7.345704512
51	0.00070	199.776826	7.79129621

Direction - Upstream Towards Fan Cooler

Flow Elem	Delta-T (s)	Force (lbf)	Impulse (lbf-s)
41	0.00204	580.08531	22.62332709
40	0.00039	110.143623	4.29560131
39(!)	0.00040	112.474353	4.386499766
38(&)	0.00014	38.8232965	1.514108563
37	0.00038	62.0249509	2.418973084
36($)	0.00087	143.519272	5.597251614
35(*)	0.00014	15.8618905	0.618613731
34(*)	0.00037	42.9604205	1.675456399
33	0.00129	212.431609	8.284832752
32(!)	0.00108	164.332897	6.408982977
31(!)	0.00053	79.9457336	3.117883611
30(!)	0.00053	79.9457336	3.117883611

Notes: All other flow elements are assumed to be 90-degree elbows
(*) - denotes the flow element as a 45-degree elbow
(#) - denotes the flow element as a 30-degree elbow
(@) - denotes the flow element as a 55-degree elbow
(!) - denotes the flow element as a reducing tee
(^) - denotes the flow element as flow orifice
($) - denotes the flow element as a flow control valve
(&) - denotes the flow element as a 8" x 6" reducer

POINT BEACH CFC1C INPUTS:

Wave Speed (C) =	4274	ft/s				
Rise Time =	0.039	sec				
Duration =	0.118	sec				
Peak Pressure =	222	psia		Rate =	=C6/C4	psi/sec
Area (8" line)	50	sq in				
Area (6" line)	28.89	sq in				
Area (2.5" line)	4.79	sq in				
Trans. Coeff. (elbows) =	1					
Trans. Coeff. (8" x 6") =	=2*C7/(C7+C7+C8)					
Trans. Coeff. (6" x 2.5") =	=2*C8/(C8+C8+C9)					

Direction - Downstream Towards

Flow Element	Pipe Area (sq in)	Length (ft)	P1 -time	P2 -time	P3 -time	P4 - time	P5 -time
42	50	0.65	0	=C17/C3	=E17+C4	=E17+(C5-C4)	=E17+C5
43	50	8.035	0	=(C17+C18)/C3	=E18+C4	=E18+(C5-C4)	=E18+C5
44	50	5.3	0	=(C17+C18+C19)/C3	=E19+C4	=E19+(C5-C4)	=E19+C5
45	50	11	0	=(C17+C18+C19+C20)/C3	=E20+C4	=E20+(C5-C4)	=E20+C5
46	50	11	0	=(C17+C18+C19+C20+C21)/C3	=E21+C4	=E21+(C5-C4)	=E21+C5
47	50	22	0	=(C17+C18+C19+C20+C21+C22)/C3	=E22+C4	=E22+(C5-C4)	=E22+C5
48	50	11	0	=(C17+C18+C19+C20+C21+C22+C23)/C3	=E23+C4	=E23+(C5-C4)	=E23+C5
49	50	15	0	=(C17+C18+C19+C20+C21+C22+C23+C24)/C3	=E24+C4	=E24+(C5-C4)	=E24+C5
50	50	4	0	=(C17+C18+C19+C20+C21+C22+C23+C24+C25)/C3	=E25+C4	=E25+(C5-C4)	=E25+C5
51	50	3	0	=(C17+C18+C19+C20+C21+C22+C23+C24+C25+C26)/C3	=E26+C4	=E26+(C5-C4)	=E26+C5

Direction - Upstream Towards Fs

Flow Element	Pipe Area (sq in)	Length (ft)	P1 -time	P2 -time	P3 -time	P4 -time	P5 -time
41	50	8.711	0	=C31/C3	=E31+C4	=E31+(C5-C4)	=E31+C5
40	50	1.654	0	=(C31+C32)/C3	=E32+C4	=E32+(C5-C4)	=E32+C5
39	50	1.689	0	=(C31+C32+C33)/C3	=E33+C4	=E33+(C5-C4)	=E33+C5
38	50	0.583	0	=(C31+C32+C33+C34)/C3	=E34+C4	=E34+(C5-C4)	=E34+C5
37	=C8	1.612	0	=(C31+C32+C33+C34+C35)/C3	=E35+C4	=E35+(C5-C4)	=E35+C5
36	=C8	3.73	0	=(C31+C32+C33+C34+C35+C36)/C3	=E36+C4	=E36+(C5-C4)	=E36+C5
35	=C8	0.583	0	=(C31+C32+C33+C34+C35+C36+C37)/C3	=E37+C4	=E37+(C5-C4)	=E37+C5
34	=C8	1.579	0	=(C31+C32+C33+C34+C35+C36+C37+C38)/C3	=E38+C4	=E38+(C5-C4)	=E38+C5
33	=C8	5.521	0	=(C31+C32+C33+C34+C35+C36+C37+C38+C39)/C3	=E39+C4	=E39+(C5-C4)	=E39+C5
32	28.89	4.625	0	=(C31+C32+C33+C34+C35+C36+C37+C38+C39+C40)/C3	=E40+C4	=E40+(C5-C4)	=E40+C5
31	28.89	2.25	0	=(C31+C32+C33+C34+C35+C36+C37+C38+C39+C40+C41)/C3	=E41+C4	=E41+(C5-C4)	=E41+C5
30	28.89	2.25	0	=(C31+C32+C33+C34+C35+C36+C37+C38+C39+C40+C41+C42)/C3	=E42+C4	=E42+(C5-C4)	=E42+C5

Direction - Downstream Towards

Flow Element	Delta-Time (s)	Force (lbf)	Impulse (lbf-s)
42	=E17	=B46*F6*B17	=C46*C4

43	=E18-E17	=B47*F6*B18	=C47*C4
44	=E19-E18	=B48*F6*B19	=C48*C4
45	=E20-E19	=B49*F6*B20	=C49*C4
46(^)	=E21-E20	=B50*F6*B21	=C50*C4
47(@)	=E22-E21	=B51*F6*B22*COS(35*PI()/180)	=C51*C4
48	=E23-E22	=B52*F6*B23	=C52*C4
49(*)	=E24-E23	=B53*F6*B24*COS(45*PI()/180)	=C53*C4
50(*)	=E25-E24	=B54*F6*B25*COS(45*PI()/180)	=C54*C4
51	=E26-E25	=B55*F6*B26	=C55*C4

Direction - Upstream Towards F

Flow Elem	**Delta-T (s)**	**Force (lbf)**	**Impulse (lbf-s)**
41	=E31	=B59*F6*B31	=C59*C4
40	=E32-E31	=B60*F6*B32	=C60*C4
39(!)	=E33-E32	=B61*F6*B33	=C61*C4
38(&)	=E34-E33	=B62*F6*B34	=C62*C4
37	=E35-E34	=B63*F6*B35	=C63*C4
36($)	=E36-E35	=B64*F6*B36	=C64*C4
35(*)	=E37-E36	=B65*F6*B37*COS(45*PI()/180)	=C65*C4
34(*)	=E38-E37	=B66*F6*B38*COS(45*PI()/180)	=C66*C4
33	=E39-E38	=B67*F6*B39	=C67*C4
32(!)	=E40-E39	=B68*F6*B40*C12	=C68*C4
31(!)	=E41-E40	=B69*F6*B41*C12	=C69*C4
30(!)	=E42-E41	=B70*F6*B42*C12	=C70*C4

Notes: All other flow elements ar
(*) - denotes the flow element as a
(#) - denotes the flow element as a
(@) - denotes the flow element as a
(!) - denotes the flow element as a
(^) - denotes the flow element as f
($) - denotes the flow element as a
(&) - denotes the flow element as a

APPENDIX H

EPRI TBR MAX FORCE/IMPULSE CALCULATIONS
FOR POINT BEACH CFC 2B
USING MICROSFOT EXCEL 97

POINT BEACH CFC2B INPUTS:

Wave Speed (C) =	4274	ft/s			
Rise Time =	0.039	sec			
Duration =	0.157	sec			
Peak Pressure =	223	psia	Rate =	5717.948718	psi/sec
Area (8" line)	50	sq in			
Area (6" line)	28 89	sq in			
Area (2.5" line)	4.79	sq in			
Trans. Coeff. (elbows) =	1				
Trans. Coeff. (8" x 6") =	0.7759				
Trans. Coeff. (6" x 2.5") =	0.9234				

Direction - Downstream Towards Throttle Valve

Flow Element	Pipe Area (sq in)	Length (ft)	P1 -time	P2 -time	P3 -time	P4 - time	P5 -time
41	50	10.33	0	0.00242	0.04142	0.12042	0.15942
42	50	13	0	0.00546	0.04446	0.12346	0.16246
43	50	6	0	0.00686	0 04586	0.12486	0.16386
44	50	6.2	0	0.00831	0.04731	0.12631	0.16531
45	50	36	0	0.01674	0.05574	0.13474	0.17374
46	50	7	0	0.01837	0.05737	0.13637	0.17537
47	50	5	0	0.01954	0.05854	0.13754	0.17654
48	50	17.1	0	0.02354	0.06254	0.14154	0.18054
49	50	7	0	0.02518	0.06418	0.14318	0.18218
50	50	24	0	0.03080	0.06980	0.14880	0.18780
51	50	2	0	0.03127	0.07027	0.14927	0.18827
52	50	1	0	0.03150	0.07050	0.14950	0.18850
53	50	14.1	0	0.03480	0.07380	0.15280	0.19180

Direction - Upstream Towards Fan Cooler

Flow Element	Pipe Area (sq in)	Length (ft)	P1 -time	P2 -time	P3 -time	P4 -time	P5 -time
40	50	1.16	0	0.00027	0.03927	0.11827	0.15727
39	50	13.063	0	0.00333	0.04233	0.12133	0.16033
38	28.89	2.167	0	0.00383	0.04283	0.12183	0.16083
37	28.89	6.5	0	0.00536	0.04436	0.12336	0.16236
36	28.89	2.25	0	0.00588	0.04488	0.12388	0.16288
35	28.89	2.25	0	0.00641	0.04541	0.12441	0.16341

Direction - Downstream Towards Throttle Valve

Flow Element	Delta-Time (s)	Force (lbf)	Impulse (lbf-s)
41	0.00215	613.401845	23.92267197
42	0.00304	869.599127	33.91436593
43	0.00140	401.353443	15.65278428
44(#)	0.00145	359.168353	14.00756578
45	0.00842	2408.12066	93.91670566
46	0.00164	468.245684	18.26158166
47	0.00117	334.461203	13.0439869
48	0.00400	1143.85731	44.61043519
49	0.00164	468.245684	18.26158166
50(@)	0.00562	1298.80702	50.65347396
51	0.00047	133.784481	5.217594759
52(*)	0.00023	47.2999569	1.844698318

53	0.00330	943.180591	36.78404305

Direction - Upstream Towards Fan Cooler

Flow Elem	Delta-T (s)	Force (lbf)	Impulse (lbf-s)
40	0.00027	77.594999	3.02620496
39(!)	0.00306	677.95278	26.44015841
38	0.00051	83.7552793	3.266455894
37(!)	0.00152	194.915965	7.601722646
36(!)	0.00053	62.3057254	2.429923292
35(!)	0.00053	62.3057254	2.429923292

Notes: All other flow elements are assumed to be 90-degree elbows
(*) - denotes the flow element as a 45-degree elbow
(#) - denotes the flow element as a 30-degree elbow
(@) - denotes the flow element as a 36-degree elbow
(!) - denotes the flow element as a reducing tee

POINT BEACH CFC2B IN

Wave Speed (C) =	4274	ft/s			
Rise Time =	0 039	sec			
Duration =	0 157	sec			
Peak Pressure =	223	psia	Rate =	=C6/C4	psi/sec
Area (8" line)	50	sq in			
Area (6" line)	28 89	sq in			
Area (2 5" line)	4.79	sq in			
Trans Coeff. (elbows) =	1				
Trans. Coeff. (8" x 6") =	=2*C7/(C7+C7+C8)				
Trans Coeff. (6" x 2 5") =	=2*C8/(C8+C8+C9)				

Direction - Downstream

Flow Element	Pipe Area (sq in)	Length (ft)	P1 -time	P2 -time	P3 -time	P4 - time	P5 -time
41	50	10 33	0	=C17/C3	=E17+C4	=E17+(C5-C4)	=E17+C5
42	50	13	0	=(C17+C18)/C3	=E18+C4	=E18+(C5-C4)	=E18+C5
43	50	6	0	=(C17+C18+C19)/C3	=E19+C4	=E19+(C5-C4)	=E19+C5
44	50	6 2	0	=(C17+C18+C19+C20)/C3	=E20+C4	=E20+(C5-C4)	=E20+C5
45	50	36	0	=(C17+C18+C19+C20+C21)/C3	=E21+C4	=E21+(C5-C4)	=E21+C5
46	50	7	0	=(C17+C18+C19+C20+C21+C22)/C3	=E22+C4	=E22+(C5-C4)	=E22+C5
47	50	5	0	=(C17+C18+C19+C20+C21+C22+C23)/C3	=E23+C4	=E23+(C5-C4)	=E23+C5
48	50	17.1	0	=(C17+C18+C19+C20+C21+C22+C23+C24)/C3	=E24+C4	=E24+(C5-C4)	=E24+C5
49	50	7	0	=(C17+C18+C19+C20+C21+C22+C23+C24+C25)/C3	=E25+C4	=E25+(C5-C4)	=E25+C5
50	50	24	0	=(C17+C18+C19+C20+C21+C22+C23+C24+C25+C26)/C3	=E26+C4	=E26+(C5-C4)	=E26+C5
51	50	2	0	=(C17+C18+C19+C20+C21+C22+C23+C24+C25+C26+C27)/C3	=E27+C4	=E27+(C5-C4)	=E27+C5
52	50	1	0	=(C17+C18+C19+C20+C21+C22+C23+C24+C25+C26+C27+C28)/C3	=E28+C4	=E28+(C5-C4)	=E28+C5
53	50	14 1	0	=(C17+C18+C19+C20+C21+C22+C23+C24+C25+C26+C27+C28+C29)/C3	=E29+C4	=E29+(C5-C4)	=E29+C5

Direction - Upstream To

Flow Element	Pipe Area (sq in)	Length (ft)	P1 -time	P2 -time	P3 -time	P4 -time	P5 -time
40	50	1.16	0	=C34/C3	=E34+C4	=E34+(C5-C4)	=E34+C5
39	50	13 063	0	=(C34+C35)/C3	=E35+C4	=E35+(C5-C4)	=E35+C5
38	28 89	2 167	0	=(C34+C35+C36)/C3	=E36+C4	=E36+(C5-C4)	=E36+C5
37	28 89	6 5	0	=(C34+C35+C36+C37)/C3	=E37+C4	=E37+(C5-C4)	=E37+C5
36	=C8	2 25	0	=(C34+C35+C36+C37+C38)/C3	=E38+C4	=E38+(C5-C4)	=E38+C5
35	=C8	2 25	0	=(C34+C35+C36+C37+C38+C39)/C3	=E39+C4	=E39+(C5-C4)	=E39+C5

Direction - Downstream

Flow Element	Delta-Time (s)	Force (lbf)	Impulse (lbf-s)
41	=E17-E34	=B44*F6*B17	=C44*C4
42	=E18-E17	=B45*F6*B18	=C45*C4
43	=E19-E18	=B46*F6*B19	=C46*C4
44(#)	=E20-E19	=B47*F6*B20*COS(30*PI()/180)	=C47*C4
45	=E21-E20	=B48*F6*B21	=C48*C4
46	=E22-E21	=B49*F6*B22	=C49*C4
47	=E23-E22	=B50*F6*B23	=C50*C4
48	=E24-E23	=B51*F6*B24	=C51*C4
49	=E25-E24	=B52*F6*B25	=C52*C4
50(@)	=E26-E25	=B53*F6*B26*COS(36*PI()/180)	=C53*C4

51	=E27-E26	=B54*F6*B27	=C54*C4
52(*)	=E28-E27	=B55*F6*B28*COS(45*PI()/180)	=C55*C4
53	=E29-E28	=B56*F6*B29	=C56*C4

Direction - Upstream To

Flow Elem	**Delta-T (s)**	**Force (lbf)**	**Impulse (lbf-s)**
40	=E34	=B60*F6*B34	=C60*C4
39(!)	=E35-E34	=B61*F6*B35*C11	=C61*C4
38	=E36-E35	=B62*F6*B36	=C62*C4
37(!)	=E37-E36	=F6*B63*B37*C11	=C63*C4
36(!)	=E38-E37	=B64*F6*B38*C11*C12	=C64*C4
35(!)	=E39-E38	=B65*F6*B39*C11*C12	=C65*C4

Notes: All other flow ele
(*) - denotes the flow elem
(#) - denotes the flow elen
(@) - denotes the flow ele
(!) - denotes the flow elem

APPENDIX I

EPRI TBR MAX FORCE/IMPULSE CALCULATIONS FOR POINT BEACH CFC 2D USING MICROSOFT EXCEL 97

POINT BEACH CFC2D INPUTS:

Wave Speed (C) =	4274	ft/s			
Rise Time =	0 028	sec			
Duration =	0.147	sec			
Peak Pressure =	286	psia	Rate =	10214.3	psi/sec
Area (8" line)	50	sq in			
Area (6" line)	28 89	sq in			
Area (2.5" line)	4.79	sq in			
Trans. Coeff. (elbows) =	1				
Trans. Coeff. (8" x 6") =	0.7759				
Trans. Coeff. (6" x 2.5") =	0.9234				

Direction - Downstream Towards Throttle Valve

Flow Element	Pipe Area (sq in)	Length (ft)	P1 -time	P2 -time	P3 -time	P4 - time	P5 -time
48	50	6 85	0	0.00160	0.02960	0.12060	0.14860
49	50	9	0	0.00371	0.03171	0.12271	0.15071
50	50	7	0	0.00535	0.03335	0.12435	0 15235
51	50	6	0	0.00675	0.03475	0.12575	0.15375
52	50	8	0	0.00862	0.03662	0.12762	0.15562
53	50	4.3	0	0.00963	0.03763	0.12863	0.15663
54	50	7	0	0.01127	0.03927	0.13027	0.15827
55	50	40	0	0.02062	0.04862	0.13962	0.16762
56	50	9	0	0.02273	0.05073	0.14173	0.16973
57	50	6.9	0	0.02434	0.05234	0.14334	0.17134
58	50	4	0	0.02528	0.05328	0.14428	0.17228
59	50	37.2	0	0.03398	0.06198	0.15298	0.18098
60	50	3	0	0.03469	0.06269	0.15369	0.18169
61	50	2.9	0	0.03536	0.06336	0.15436	0.18236
62	50	12.9	0	0.03838	0.06638	0.15738	0.18538

Direction - Upstream Towards Fan Cooler

Flow Element	Pipe Area (sq in)	Length (ft)	P1 -time	P2 -time	P3 -time	P4 -time	P5 -time
47	50	2.75	0	0.00064	0.02864	0.11964	0.14764
46	50	3.667	0	0.00150	0.02950	0.12050	0.14850
45	28.89	6.438	0	0.00301	0.03101	0.12201	0.15001
44	28.89	3.667	0	0.00387	0.03187	0.12287	0.15087
43	28.89	3.667	0	0.00472	0.03272	0.12372	0.15172
42	28.89	5.625	0	0.00604	0.03404	0.12504	0.15304
41	28.89	2.25	0	0.00657	0.03457	0.12557	0.15357
40	28.89	2.25	0	0.00709	0.03509	0.12609	0.15409

Direction - Downstream Towards Throttle Valve

Flow Element	Delta-Time (s)	Force (lbf)	Impulse (lbf-s)
48	0.00160	818.5289792	22.91881142
49	0.00211	1075.439535	30.11230697
50	0.00164	836.4529715	23.4206832
51	0.00140	716.9596898	20.07487131
52(*)	0.00187	675.956078	18.92677018
53(*)	0.00101	363.3263919	10.17313897
54	0.00164	836.4529715	23.4206832
55	0.00936	4779.731265	133.8324754
56	0.00211	1075.439535	30.11230697
57(*)	0.00161	583.0121173	16.32433928
58	0.00094	477.9731265	13.38324754
59(#)	0.00870	3596.201955	100.6936547

60	0.00070	358 4798449	10 03743566
61(*)	0 00068	245 0340783	6 860954192
62	0.00302	1541.463333	43.16097333

stream Towards Fan Cooler

Flow Elem	Delta-T (s)	Force (lbf)	Impulse (lbf-s)
47	0.00064	328 6065245	9.200982686
46	0.00086	438 1818638	12.26909219
45(!)	0.00151	344.8679016	9.656301244
44(S)	0.00086	196.4322142	5.500101998
43	0.00086	196 4322142	5.500101998
42(!)	0.00132	278 250345	7.791009659
41(!)	0.00053	111.300138	3.116403864
40(!)	0.00053	111.300138	3.116403864

Notes:

(*) - denotes the flow element as a 45-degree elbow
(#) - denotes the flow element as a 36-degree elbow
(!) - denotes the flow element as a reducing tee
(S) - denotes the flow element as a flow control valve

POINT BEACH CFC2D INPUTS

Wave Speed (C) =	4274	ft/s			
Rise Time =	0 028	sec			
Duration =	0 147	sec			
Peak Pressure =	286	psia	Rate =	=C6/C4	psi/sec
Area (8" line)	50	sq in			
Area (6" line)	28 89	sq in			
Area (2 5" line)	4 79	sq in			
Trans Coeff (elbows) =	1				
Trans Coeff (8" x 6") =	=2*C7/(C7+C7+C8)				
Trans Coeff. (6" x 2 5") =	=2*C8/(C8+C8+C9)				

Direction - Downstream Towai

Flow Element	Pipe Area (sq in)	Length (ft)	P1 -time	P2 -time	P3 -time	P4 - time	P5 -time
48	50	6 85	0	=C17/C3	=E17+C4	=E17+(C5-C4)	=E17+C5
49	50	9	0	=(C17+C18)/C3	=E18+C4	=E18+(C5-C4)	=E18+C5
50	50	7	0	=(C17+C18+C19)/C3	=E19+C4	=E19+(C5-C4)	=E19+C5
51	50	6	0	=(C17+C18+C19+C20)/C3	=E20+C4	=E20+(C5-C4)	=E20+C5
52	50	8	0	=(C17+C18+C19+C20+C21)/C3	=E21+C4	=E21+(C5-C4)	=E21+C5
53	50	4 3	0	=(C17+C18+C19+C20+C21+C22)/C3	=E22+C4	=E22+(C5-C4)	=E22+C5
54	50	7	0	=(C17+C18+C19+C20+C21+C22+C23)/C3	=E23+C4	=E23+(C5-C4)	=E23+C5
55	50	40	0	=(C17+C18+C19+C20+C21+C22+C23+C24)/C3	=E24+C4	=E24+(C5-C4)	=E24+C5
56	50	9	0	=(C17+C18+C19+C20+C21+C22+C23+C24+C25)/C3	=E25+C4	=E25+(C5-C4)	=E25+C5
57	50	6 9	0	=(C17+C18+C19+C20+C21+C22+C23+C24+C25+C26)/C3	=E26+C4	=E26+(C5-C4)	=E26+C5
58	50	4	0	=(C17+C18+C19+C20+C21+C22+C23+C24+C25+C26+C27)/C3	=E27+C4	=E27+(C5-C4)	=E27+C5
59	50	37 2	0	=(C17+C18+C19+C20+C21+C22+C23+C24+C25+C26+C27+C28)/C3	=E28+C4	=E28+(C5-C4)	=E28+C5
60	50	3	0	=(C17+C18+C19+C20+C21+C22+C23+C24+C25+C26+C27+C28+C29)/C3	=E29+C4	=E29+(C5-C4)	=E29+C5
61	50	2 9	0	=(C17+C18+C19+C20+C21+C22+C23+C24+C25+C26+C27+C28+C29+C30)/C3	=E30+C4	=E30+(C5-C4)	=E30+C5
62	50	12 9	0	=(C17+C18+C19+C20+C21+C22+C23+C24+C25+C26+C27+C28+C29+C30+C31)/C3	=E31+C4	=E31+(C5-C4)	=E31+C5

Direction - Upstream Towards

Flow Element	Pipe Area (sq in)	Length (ft)	P1 -time	P2 -time	P3 -time	P4 -time	P5 -time
47	50	2.75	0	=C36/C3	=E36+C4	=E36+(C5-C4)	=E36+C5
46	50	3 667	0	=(C36+C37)/C3	=E37+C4	=E37+(C5-C4)	=E37+C5
45	28 89	6 438	0	=(C36+C37+C38)/C3	=E38+C4	=E38+(C5-C4)	=E38+C5
44	28 89	3 667	0	=(C36+C37+C38+C39)/C3	=E39+C4	=E39+(C5-C4)	=E39+C5
43	=C8	3 667	0	=(C36+C37+C38+C39+C40)/C3	=E40+C4	=E40+(C5-C4)	=E40+C5
42	=C8	5 625	0	=(C36+C37+C38+C39+C40+C41)/C3	=E41+C4	=E41+(C5-C4)	=E41+C5
41	=C8	2 25	0	=(C36+C37+C38+C39+C40+C41+C42)/C3	=E42+C4	=E42+(C5-C4)	=E42+C5
40	=C8	2 25	0	=(C36+C37+C38+C39+C40+C41+C42+C43)/C3	=E43+C4	=E43+(C5-C4)	=E43+C5

Direction - Downstream Towai

Flow Element	Delta-Time (s)	Force (lbf)	Impulse (lbf-s)
48	=E17	=B47*F6*B17	=C47*C4
49	=E18-E17	=B48*F6*B18	=C48*C4
50	=E19-E18	=B49*F6*B19	=C49*C4
51	=E20-E19	=B50*F6*B20	=C50*C4
52(*)	=E21-E20	=B51*F6*B21*COS(45*PI()/180)	=C51*C4
53(*)	=E22-E21	=B52*F6*B22*COS(45*PI()/180)	=C52*C4
54	=E23-E22	=B53*F6*B23	=C53*C4
55	=E24-E23	=B54*F6*B24	=C54*C4
56	=E25-E24	=B55*F6*B25	=C55*C4
57(*)	=E26-E25	=B56*F6*B26*COS(45*PI()/180)	=C56*C4
58	=E27-E26	=B57*F6*B27	=C57*C4

59(#)	=E28-E27	=B58*F6*B28*COS(36*PI()/180)	=C58*C4
60	=E29-E28	=B59*F6*B29	=C59*C4
61(*)	=E30-E29	=B60*F6*B30*COS(45*PI()/180)	=C60*C4
62	=E31-E30	=B61*F6*B31	=C61*C4

Direction - Upstream Towards

Flow Elem	Delta-T (s)	Force (lbf)	Impulse (lbf-s)
47	=E36	=B65*F6*B36	=C65*C4
46	=E37-E36	=B66*F6*B37	=C66*C4
45(!)	=E38-E37	=B67*F6*B38*C11	=C67*C4
44($)	=E39-E38	=F6*B68*B39*C11	=C68*C4
43	=E40-E39	=B69*F6*B40*C11	=C69*C4
42(!)	=E41-E40	=B70*F6*B41*C11*C12	=C70*C4
41(!)	=E42-E41	=B71*F6*B42*C11*C12	=C71*C4
40(!)	=E43-E42	=B72*F6*B43*C11*C12	=C72*C4

Notes:

(*) - denotes the flow element as
(#) - denotes the flow element as
(!) - denotes the flow element as
($) - denotes the flow element as