EPRI

Generic Letter 96-06 Waterhammer Issues Resolution

Technical Basis Report - Non Proprietary

Technical Report

Generic Letter 96-06
Waterhammer Issues Resolution

Technical Basis Report – Non Proprietary

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EPRI Project Manager
A. Singh

EPRI • 3412 Hillview Avenue, Palo Alto, California 94304 • PO Box 10412, Palo Alto, California 94303 • USA
800.313.3774 • 650.855.2121 • askepri@epri.com • www.epri.com

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CITATIONS

This report was prepared by

Altran Corporation
451 D Street, FL 6
Boston, MA 02210-1950

Principal Investigators
G. Zysk
T. C. Esselman
D. A. Van Duyne

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REPORT SUMMARY

The U.S. Nuclear Regulatory Commission (NRC) Generic Letter 96-06 identified potential issues for waterhammer effects during postulated events that can cause potential damage to service water systems. The User's Manual (Volume 1) provides methods recommended for evaluating the impact of potential waterhammer loads on plant service water system components. This Technical Basis Report (Volume 2) provides detailed background information and the technical basis for the methods defined in the User's Manual.

Background

Following either a Loss of Coolant Accident (LOCA) or a Main Steam Line Break (MSLB) concurrent with a Loss of Offsite Power (LOOP), pumps that supply cooling water to fan cooler units (FCUs) and fans that supply air to FCUs will temporarily lose power. Cooling water flow will stop due to the loss of pump head. Boiling may occur in FCU tubes, causing steam bubbles to form in FCUs and pass into the attached piping, creating steam voids. As service water pumps restart, accumulated steam in the fan cooler tubes and piping will condense and pumped water can produce a waterhammer when the void closes. Hydrodynamic loads introduced by such a waterhammer event could potentially challenge the integrity and function of FCUs and associated cooling water system components, as well as pose a potential challenge to containment integrity.

Objective

To provide a technical approach, benchmarked against test data, for evaluating potential waterhammer loads and their impact on service water systems anticipated during event scenarios identified in NRC Generic Letter 96-06.

Approach

A testing and analysis program was undertaken to develop methods for realistic evaluation of waterhammer loads. The program's scope was designed and validated using a Phenomena Identification and Ranking Table (PIRT) assessment. The program focused on fluid condition characteristics for this specific event. Conditions included low system pressure, non-condensables in the water, a low and controlled velocity of column closure, and a thermal layer (a hot layer of water in contact with accumulated steam). The testing program included several types of tests: column closure tests designed to simulate plant conditions, condensation-induced waterhammer tests, and gas release rate tests. The tests characterized the waterhammer pressure pulse, pressure wave propagation in the pipe, and reaction of the pressure transient in prototypical piping supports.

Results

The primary conclusions from the project are the following:

- Waterhammers produced by a LOOP-only event will be more severe than those produced by a LOOP/LOCA or LOOP/MSLB event if voiding occurs during a LOOP alone and if the system valve and pump operation is the same as the LOOP/LOCA or LOOP/MSLB.
- Condensation-induced waterhammer events (CIWH) are limited in magnitude and duration in low-pressure service water systems and do not create a limiting transient, particularly in systems that experience CCWH.
- Non-condensables (air or nitrogen) in the void diminish the severity of the waterhammer events.
- Column Closure Waterhammer (CCWH) events can be evaluated using Method of Characteristics or Rigid Body Model methods considering steam and non-condensables pressurization in the void.
- A simplified, trapezoidal characterization of the pressure-time history can be used to produce a conservative structural loading of the piping system.

EPRI Perspective

The testing and analyses performed within the framework of this program demonstrate that waterhammers following a LOOP and LOCA (or MSLB) are not as severe as originally believed. Methods are provided for evaluating and qualifying systems that contain fan coolers. These methods, and supporting verification, provide realistic predictions that can assure plant safety and minimize plant modifications. Example applications to both an open-loop and a closed-loop service water system are included to help facilitate applications by utility engineers. Although the report's focus has been on issues identified in GL96-06, this technical approach can be used to evaluate similar waterhammers that could occur from water column closures in other than service water systems.

When used for resolution of Generic letter 96-06 issues on a specific plant basis, the information contained in this report must be used in a manner that is consistent with the requirements specified by NRC staff. A copy of the NRC Safety Evaluation Report and supporting EPRI correspondence to NRC are included in the appendices to this report. Additional guidance or restrictions required by NRC staff are not included in this document.

Keywords

Reactor safety and licensing
Waterhammer
Piping loads

ABSTRACT

A testing and analysis program was undertaken to develop a technical approach, benchmarked against test data, for evaluating potential waterhammer loads and their impact on service water systems anticipated during event scenarios identified in NRC Generic Letter 96-06. The program's scope was designed and validated using a Phenomena Identification and Ranking Table (PIRT) assessment. Conditions that were evaluated included low system pressure, non-condensables in the water, a low and controlled velocity of column closure, and a thermal layer (a hot layer of water in contact with accumulated steam). The testing and analyses performed within the framework of this program demonstrate that waterhammers following a LOOP and LOCA (or MSLB) are not as severe as originally believed. Methods are provided for evaluating and qualifying systems that contain fan coolers. These methods, and supporting verification, provide realistic predictions that can assure plant safety and minimize plant modifications. Example applications to both an open-loop and a closed-loop service water system are included to help facilitate applications by utility engineers. Although the report's focus has been on issues identified in GL96-06, this technical approach can be used to evaluate similar waterhammers that could occur from water column closures in other than service water systems.

When used for resolution of Generic letter 96-06 issues on a specific plant basis, the information contained in this report must be used in a manner that is consistent with the requirements specified by NRC staff. Additional guidance or restrictions required by NRC staff are not included in this document.

ACKNOWLEDGMENTS

The technical work described in this report was performed with valuable guidance and inputs from the Waterhammer Expert Panel consisting of Professor Peter Griffith of MIT, Dr. Fred Moody (Consultant) and Dr. Ben Wylie of the University of Michigan. Dr. Robert Henry and Mr. Robert Hammersley of Fauske and Associates performed work on the project, provided valuable input, and data that were used to develop the positions. The overall project direction and funding was provided by the Waterhammer Utility Advisory Group consisting of the following:

Wagoner, Vaughn, Chairman	Carolina Power & Light
Azzarello, Leonard	Duke Energy
Brown, Timothy	Duke Energy
Chang, Hsin-Yung	New York Power Authority
Connor, Todd	Baltimore Gas & Electric
Conry, Marlin	Wisconsin Electric
Cozens, Kurt	Nuclear Energy Institute
Fish, Hamilton	New York Power Authority
Ginsberg, Art	Consolidated Edison
Hayes, Roger	Southern Nuclear Operating Company
Husaini, Mahmood	Southern California Edison
Kemp, Brian	Wisconsin Electric
Malone, Dan	Consumers Energy
Myer, Chalmer	Southern Company Services
Qashu, Riyad	Southern California Edison
Randels, Raub	ComEd
Ray, Dillip	Southern Nuclear Operating Company
Riat, Dharam S.	Consumers Energy
Robinson, Mike	Duke Energy
Rochino, Lee	Rochester Gas & Electric
Thomas, Steve	Northern States Power
Webb, Thomas	Wisconsin Public Service

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EXPERT PANEL REVIEW OF THE EPRI REPORTS

The undersigned have worked independently as an "Expert Panel" with the team that has prepared this report. The objective of the Expert Panel efforts was to perform an independent review of the Technical Basis Report (TBR) and User's Manual to support their technical completeness and adequacy to resolve the questions raised by NRC's Generic Letter 96-06.

The Expert Panel consisted of three members – Dr. Peter Griffith, Chairman, Dr. Fred Moody, and Dr. Benjamin Wylie. The Expert Panel participated in four review meetings attended by sponsoring utilities, EPRI, and EPRI's contractor Altran Corporation. The NRC staff and their consultants participated in two of these review meetings. In addition, the Expert Panel members were involved in periodic individual reviews of the draft contents of the TBR during its development. Guidance was provided as requested throughout the project.

The panel performed a review of the overall project plan, the approach for resolving individual issues raised by the NRC, the test plans and the tests performed, data analysis, analysis method development, and conclusions drawn in the Technical Basis Report (TBR).

The Expert Panel has completed its review of the TBR and associated User's Manual. We provide the following conclusions:

- The Expert Panel agrees that the PIRT analysis performed has identified all important phenomena and processes that may impact the waterhammer loads during the transients identified in Generic Letter 96-06.
- The Expert Panel agrees that the technical approach documented in the TBR and User's Manual is technically justifiable and validated against appropriate data for plant application.
- The Expert Panel agrees that, considering the lack of credible threat to the safety functions and the low probability of the potential waterhammer events identified in Generic Letter 96-06, the proposed approach is conservative and uncertainties have been adequately addressed in application to plants.
- The Expert Panel agrees that the guidelines for application by a utility user are sufficiently detailed and example applications provided are representative of real plant applications.

We have been mindful during our review of the stochastic behavior of the events being considered and the overall risk to the safety of the plant. It is judged to be advantageous to be as realistic as possible, but to not compromise the evaluation of the adequacy of the systems being considered. The conservative quantification of every variable that may affect either the waterhammer or the response of the piping was not considered to be the objective of the study or our review. The overall acceptability of the system, considering the known conservatisms, led the review team to conclude that the overall conclusions were acceptable.

In summary, the Expert Panel members endorse the TBR and User's Manual as a credible technical basis for providing high assurance that the integrity of the service water systems can be maintained.

Signed by: Peter Griffith (Chairman)
Frederick J. Moody
E. Benjamin Wylie

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EXECUTIVE SUMMARY

Abstract

The United States Nuclear Regulatory Commission (NRC) Generic Letter 96-06 identified potential issues with cooling water systems following either a Loss of Coolant Accident (LOCA) or a Main Steam Line Break (MSLB) concurrent with a Loss of Offsite Power (LOOP). The potential for damage due to waterhammer associated with the postulated event was included in the Generic Letter.

Column closure and condensation induced waterhammers may occur in the fan cooler system during this transient. Piping loads produced by waterhammer must be evaluated to assure that the integrity of the system is maintained.

System Characteristics

The fan cooler systems include pumps, piping, fan cooler units (FCUs), and other in-line components such as valves and orifices. The systems in all plants are categorized as either open loop or closed loop. Open loop systems are typically found at fresh water sites. Closed loop systems are typically found at salt-water sites and BWR units. The systems are designed to remove heat from containment during a Loss of Coolant Accident (LOCA) or Main Steam Line Break (MSLB). With normal service water flow into the FCUs, the system will remain water solid.

The systems have great similarity from plant-to-plant. Open loop systems have FCUs that are generally at higher elevations in containment. The pumps are outside containment, near the raw-water source, and the FCUs, supply and discharge pipes in containment form a containment boundary. The closed loop system design is very similar to open loop plants, but there is a heat exchanger in the system and an expansion tank.

Background

If a steam void forms in a pipe containing service water, sudden collapse of the void can generate waterhammer pressure loads. Steam voids can form by depressurization (*flashing*) if a loss of offsite power (LOOP) causes pump coast down, and the corresponding loss of pump head reduces local water pressure to the saturated state at elevated points in the flow path. Voids also can be formed by heat transfer (*boiling*) if a loss of coolant accident (LOCA) or main steam line break (MSLB) raises the external temperature enough to heat the water in the FCUs to its saturation temperature.

Void formation by flashing and boiling are considered in service water scenarios associated with containment fan cooler units (FCUs) in nuclear plants. One scenario consists of a LOOP, whereby pumps coast down, causing flow velocity reduction to heat exchangers at a high elevation. So-called "open loop" plants have FCUs that discharge to a low elevation receiver at approximately atmospheric pressure, P_{atm}. If the water temperature is T, with a corresponding saturation pressure $P_{sat}(T)$, the receiver pressure can only support a water column of height corresponding to the static head H. If the heat exchanger elevation is higher than H, which is normally the case, a steam void will form from flashing. A negligible amount of non-condensable gas is released from the small amount of water that flashes in a LOOP-only scenario.

Boiling also can supply steam to the void if the LOOP is concurrent with a LOCA or MSLB. Significant quantities of non-condensable gas can be released from the larger amount of water that boils, relative to the amount of water that flashes during a depressurization. Most of the released gas will occupy the steam void, although some gas may remain in the water as small bubbles.

Open loop plants have FCUs that discharge to a low elevation receiver at atmospheric pressure, and can void due to LOOP alone. In a closed loop plants, the FCUs are in a loop with a volume control tank at a higher elevation than the FCU, so that if the pumps lose power during a LOOP, no void by flashing will form. Voids can form only from boiling in closed loop systems following a LOOP with a LOCA or MSLB.

Once voids are formed in service water piping, they can collapse once the pumps restart and the moving water column closes onto the stationary column, referred to as column closure waterhammer (CCWH). If the void has formed from flashing (LOOP-only), pump restart causes CCWH proportional to the velocity of the closing water column. If the void has formed from boiling (LOOP with LOCA or MSLB), the CCWH that will occur is influenced by the rate of steam condensation and presence of non-condensable gases in the void. These can reduce the relative velocity of impacting water columns, and consequently reduce the resulting waterhammer disturbances.

While the void is forming (prior to pump restart), void collapse can also occur if steam rapidly condensing on cooler water or pipe surfaces causes a transition to slug flow. This can occur only in horizontal pipes and is referred to as a condensation induced waterhammer (CIWH). The severity of this waterhammer is related to the pressure of the system and is reduced by non-condensable gas in the pipe at the time of the waterhammer.

Waterhammer caused by a void collapse – either a CCWH or a CIWH – generates a transient pressure disturbance in the pipe. The pressure disturbance moves in both directions from the location of the closure and causes unbalanced loads in the piping system that loads the pipe and the pipe supports.

The objective of this study is to present a technical approach for evaluating the loads on the piping and pipe supports from waterhammer caused by CCWH and CIWH. This technical approach can be used to demonstrate that the integrity of the system will be maintained in the event that these waterhammer events occur.

Condensation Induced Waterhammer

The condensation induced waterhammer (CIWH) pressure magnitude is related to the pressure in the pipe at the time of the waterhammer and is affected by the sonic velocity of the water local to the impact location, non condensables in the water and steam, and the size of the void. In the fan cooler system following a LOOP and LOCA or MSLB, non-condensables are present in the water and steam and the system pressure is low, approximately atmospheric pressure.

Analytical methods are inadequate to accurately calculate the pressure magnitude of the CIWH in the specific conditions of the service water system. Because of this, a testing program was used to determine the severity of the CIWH. Eighty-two CIWH tests were conducted, including thirty-seven tests with normally aerated water and forty-five tests with deaerated water. A summary of the tests performed in normal water, prototypical of the water expected to be in the service water system, is shown below. Pressure calculated using the Joukowski equation with an equal bubble and liquid volume (pipe half full) and a sonic velocity of 4,600 feet per second is also shown.

All the CIWH data had a relatively constant pressure impulse, determined as the area under the pressure-time curve. Higher pressure pulses had very short durations and the low magnitude pulses had longer durations. A plot of pressure magnitude versus the time duration of the pulse is shown in the figure below. A line showing constant impulse behavior is also provided. This curve also includes deaerated water test results. It can be seen that the impulse is independent of whether the water is aerated or deaerated.

Waterhammer Peak Pressure vs. Duration – Normal and Deaerated Water

The effect of the constant impulse behavior is evident in the support load response. The support loads were measured at the end of the horizontal test section and are plotted versus the peak waterhammer pressure for both normal water and deaerated water. The pipe support force is limited for waterhammer pressures above approximately 150 psig. The diminished structural response at high pressures is caused by the very brief pulse duration relative to the structural response.

The impulse for the CIWH has been compared to the pressure impulse for a typical range of column closure waterhammers. The CIWH pressure impulse is significantly less than the pressure impulse that occurs for a CCWH in the same system. It has also been shown during the tests that the waterhammer pressures are independent of the draining flow velocity and the pipe length. A scaling analysis concluded that both the waterhammer pressure rise duration and the measured absolute pressure spike in the smaller experimental pipes would be higher than the pressures expected in larger pipes.

The conclusion from the CIWH testing program was that the CIWH waterhammers, for low-pressure service water systems, are limited in magnitude and duration and do not create a limiting transient for the piping system, particularly in systems that also experience a CCWH.

Support Load vs. Waterhammer Peak Pressure – Normal and Deaerated Water

Column Closure Waterhammer

The column closure waterhammer (CCWH) occurs after the pumps are restarted and the final closure occurs. An accepted method of evaluation for CCWH is the method of characteristics (MOC). The method of characteristics includes closure velocity reduction due to potential pressurization of non-condensables and steam in the void and wave propagation effects in the fluid.

The method of characteristics method is capable of accurately analyzing the cushioning that will result from the pressurization of non-condensable gas that is accumulated in the void. Testing was required to provide information necessary to determine the steam condensation rate in the void. Condensation rate was determined by comparison of the model results to test data. Once the steam condensation rate was determined, very close correlation between the calculation of the waterhammer using the method of characteristics and the test results was achieved.

Data was also required to determine the amount of gas that would be released into the void by boiling. Gas release tests were performed that showed that approximately 50% of the gas in solution in water that is exposed to boiling would be rapidly released by boiling conditions similar to those that would exist in the FCUs during a LOCA or MSLB. A smaller amount of gas – approximately 24% – is released from the water that steam passes through.

Analyses were performed for the column closure waterhammer using both the method of characteristics and a simplified rigid body model (RBM). The rigid body model differs from the MOC in that the water column closing the void is treated as a solid mass with no wave propagation effects. The RBM was used to develop solution sets for various input parameters that were tabularized for use in plant applications. The rigid body model was shown to be conservative relative to the method of characteristics when wave reflection was taken into account. A comparison between the rigid body model and the method of characteristics is shown below.

RBM/MOC Pressure Comparison (Psig)

Both the method of characteristics and the rigid body model were correlated to test results. The following table provides results from the modeling of a specific set of test conditions using the method of characteristics, the rigid body model, and the test results.

RBM and MOC Comparison Against Test Data			
Test Case	**MOC Peak Pressure (psig)**	**RBM Peak Pressure (psig)**	**Test Data: Peak Pressure Range (psig)**
20 psig driving pressure; 20 ft column; Normal Water	[ ]	[ ]	[ ]
70 psig driving pressure; 20 ft column; Normal Water	[ ]	[ ]	[ ]
45 psig driving pressure; 3 ft column; Normal Water	[ ]	[ ]	[ ]
45 psig driving pressure; 17 ft column, Deaerated Water	[ ]	[ ]	[ ]

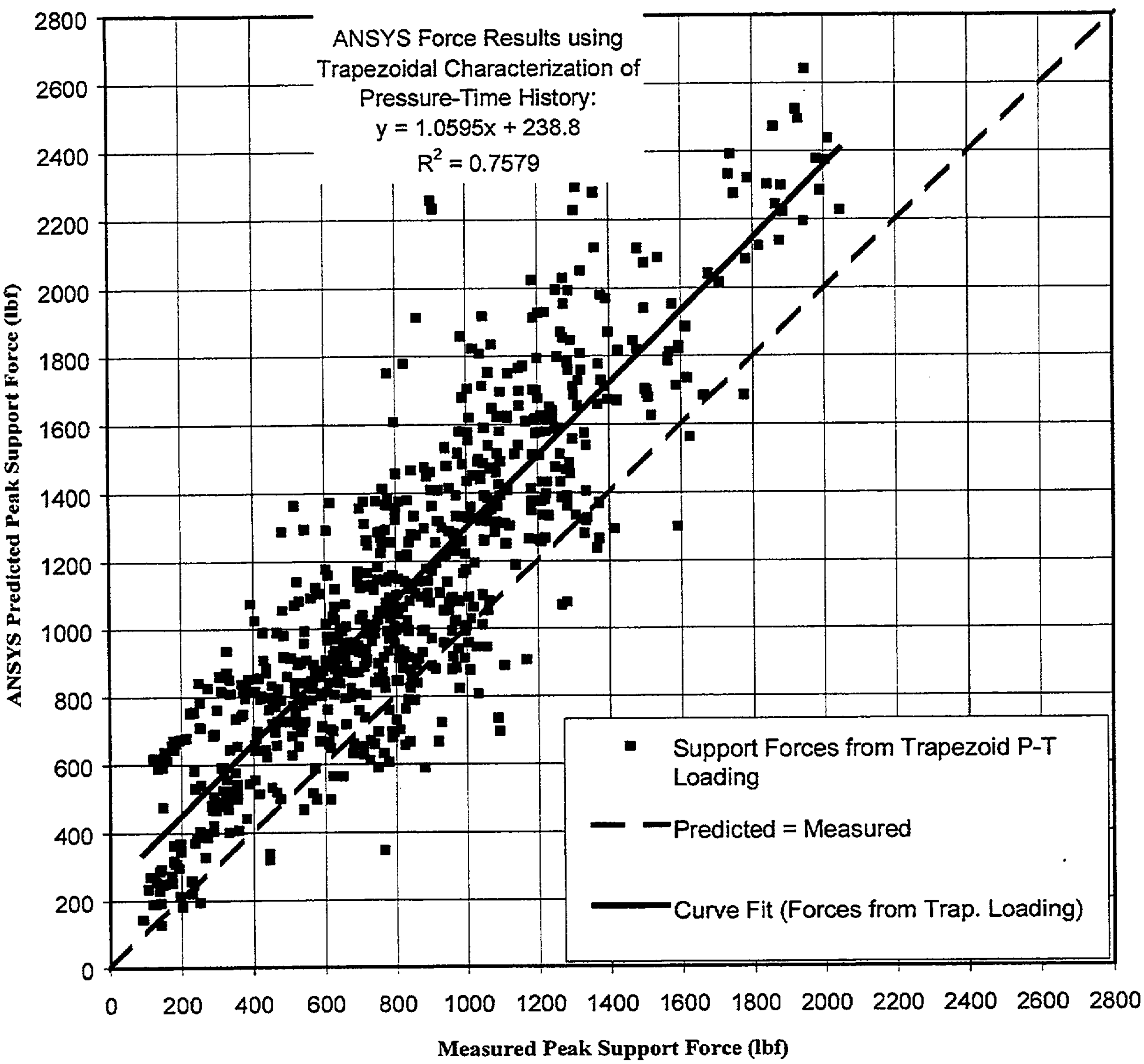
The primary conclusions from the CCWH analyses are the following:

- Pressures from CCWH are mitigated by gas and steam pressurization in the void.
- The method of characteristics provides a means of accurately simulating all aspects of pump startup in a system with vapor pockets of steam plus non-condensable gas, and it predicts the peak pressure and rise times of CCWH events.
- The reduction in velocity and the mitigation of the waterhammer can also be calculated by simplified rigid body model.

Support Loads

The support loads were measured in CCWH tests that were performed. It was determined that a simplified trapezoidal model was effective to characterize the actual pressure pulses. This trapezoidal loading was developed to reflect fundamental theory, capture the pulse magnitude, rise time, and duration, and simplify the transient pressure response into a set of defined pressure-time (P-T) points for use in a structural calculation. The effectiveness of the trapezoid model was tested by comparing 1) the response of a finite element analysis model with 2) loading from the idealized trapezoids and 3) loading with actual pressure-time histories to the measured force response from the tests.

The following plot shows the results from the trapezoidal characterization of the pulses for *all tests* analyzed using the same analytical model. These force responses are plotted versus the measured force data for three piping supports restraints. It can be seen that the trapezoidal characterization of the pressure time pulse shapes is conservative for structural modeling.



Trapezoid Characterization (All Tests)

User's Manual And Technical Basis Report

The User's Manual (UM) (Volume 1) and the Technical Basis Report (TBR) (Volume 2) provide guidance for the evaluation of potential waterhammer events resulting from postulated concurrent LOOP/LOCA or LOOP/ MSLB scenarios. These reports are not intended to replace individual plant analyses, but to provide a methodology that can assist in the calculation of the waterhammer characteristics and be used to evaluate the potential effects of waterhammer arising from the conditions described in GL96-06. The Technical Basis Report supports the methods described in the User's Manual for the evaluation of the service water system loads. The TBR presents test data, theory, and background information intended to justify the methodology and inputs provided in the User's Manual.

NOMENCLATURE

Standard Abbreviations

1. CCWH Column Closure Waterhammer
2. CIWH Condensation Induced Waterhammer
3. DLF Dynamic Load Factor
4. FCU Fan Cooler Unit
5. FSI Fluid Structural Interaction
6. LOCA Loss of Coolant Accident
7. LOOP Loss of Offsite Power
8. MOC Method of Characteristics: a finite difference technique for solving transient fluid problems
9. MSLB Main Steam Line Break
10. PIRT Phenomenon Identification and Ranking Table
11. RAI USNRC Request for Additional Information
12. RBM Rigid Body Model
13. SW Service Water
14. TBR Technical Basis Report
15. UM User's Manual

Symbols, Units, and Typical Values for Constant Terms

1. A internal cross sectional area of pipe (flow area) (in^2)
2. A_{cds} condensing surface area (ft^2)
3. A_{or} area of an orifice or flow restriction (in^2)
4. a acceleration (d^2x/dt^2) (ft/sec^2)
5. B pipeline characteristic impedance (sec/ft^2)
6. C sonic velocity (ft/sec); also used as orifice flow coefficient
7. C_f sonic velocity based on fluid compressibility (ft/sec)
8. C_{pipe} sonic velocity based on pipe flexibility (ft/sec)
9. CON_{air} mass concentration of air in water (mg/liter)
10. CON_{O2} mass concentration of oxygen in water (mg/liter)
11. c_L specific heat of a liquid (BTU/lb°R)
12. C_p specific heat (BTU/lbm°F)
13. c_{pipe} specific heat of a piping material (BTU/lb°R)
14. D pipe inside diameter (in)
15. dO_2 amount of dissolved oxygen in water (mg/L)
16. E elastic modulus (psi)
17. f pipe friction factor
18. Fr Froude number
19. g gravitational acceleration (32.2 ft/sec^2)
20. g_o gravitational acceleration constant (32.2 $ft \cdot lbm/sec^2 \cdot lbf$)
21. h height (ft); also used as condensing heat transfer coefficient ($BTU/hr \cdot ft^2 \cdot °F$)
22. h_{fg} latent heat of vaporization per unit mass (BTU/lbm)
23. h_f specific enthalpy (BTU/lbm)
24. h_{cds} condensing heat transfer coefficient ($BTU/hr \cdot ft^2 \cdot °F$)

25. H	pressure head (ft of water)
26. ID	pipe inside diameter (in)
27. I	impulse (psi·sec)
28. K	number of velocity heads (also referred to as flow coefficient) from: friction = $K \cdot V^2/2g$
29. K_{imp}	constant representing condensation induced waterhammer impulse (psi·sec)
30. K_R	constant used in curve fit for determining rise time (1/ft)
31. k	constant used in Joukowski equation to describe closure type ($k = 0.5$ for water on water closure and $k = 1.0$ for water on hard surface closure)
32. L	length of piping system (ft)
33. L_{stm}	length of steam void (ft)
34. L_w	length of water column (ft)
35. Lwo	length of water column at start of void closure (ft)
36. Lao	length of void at start of void closure (ft)
37. Le	length from closure point to a flow area expansion (ft)
38. m	mass (lb unless units of slugs are identified)
39. m'	mass flow rate (lbm/sec)
40. m'_{gf}	condensation rate
41. m'_{stm}	steam condensation rate
42. m_{air}	mass of air concentrated in the void (lb)
43. m_{cds}	mass of steam that condenses in the void (lb)
44. m_g	gas mass (lb)
45. m_{max}	maximum free gas concentration reached after the gas release activity phase per m^3 of liquid ($kg/s \cdot m^3$)
46. m_{stm}	steam mass (lb)
47. m_{rate}	mass release rate of dissolved gas per m^3 of liquid ($kg/s \cdot m^3$)
48. OD	pipe outside diameter (in)

49. P, p — pressure, can be absolute (psia) or gage (psig)

50. P_I — impact pressure (psig)

51. p_e — equilibrium or saturation pressure (psia)

52. p_g — gas pressure above the liquid (psia)

53. p_o — initial system pressure (psia)

54. P_{steam} — steam pressure driving CIWH event (psia or psig)

55. P_o — system pressure (psia or psig)

56. P_{burst} — burst pressure of pipe or tube (psi)

57. P_d — driving pressure (psia or psig)

58. P_D — design pressure (psia or psig)

59. P_{pa} — partial pressure of air (psia)

60. P_{ps} — partial pressure of steam (psia)

61. P_{sat} — saturation pressure at a specific temperature (psia or psig)

62. P_{atm} — atmospheric pressure (psia or psig)

63. P_v — void pressure (psia or psig)

64. P_{inc} — incident pressure (psia or psig)

65. PP_{air} — partial pressure of air (psi)

66. PP_{stm} — partial pressure of steam (psi)

67. P_{sys} — system pressure (psia or psig)

68. P_{tran} — transmitted pressure (psia or psig)

69. P_{ref} — reflected pressure (psia or psig)

70. ΔP — waterhammer pressure pulse (change in system pressure due to WH) (psi)

71. Q — flow rate (ft^3/sec)

72. q — heat transfer rate (BTU/hr)

73. r — gas-liquid volume ratio

74. R	gas constant (53.3 ft·lbf/lbm·°R for air); also used as pipeline resistance coefficient (sec^2/ft^3); (also used as curve fit regression coefficient and as multiplier when considering constant impulse)
75. Re	Reynolds number
76. S	solubility constant
77. S_{allow}	allowable material stress (ksi)
78. S_{ult}	ultimate material stress (ksi)
79. t	time (sec)
80. T	absolute temperature (°R) or temperature (°F); also used as period (sec)
81. t_d	time duration of pressure pulse (sec)
82. t_E	half life of evolution
83. t_r	rise time for pressure pulse (sec)
84. T_s	condensing surface temperature (°F)
85. T_{stm}	steam temperature (°F)
86. T_{pipe_o}	piping temperature at start of transient (°F)
87. V	fluid velocity (ft/sec) or void closure velocity (ft/sec)
88. V_i	impact velocity (ft/sec)
89. V_0	steady state velocity (ft/sec)
90. Vol	volume (ft^3)
91. Vol_t	void size (ft^3)
92. ΔV	velocity change (ft/sec)
93. x	axial position (ft)
94. z	collapsing void length (ft)

Greek Symbols

1. α void fraction
2. β fluid bulk modulus (psi); also used as orifice diameter ratio
3. δ pipe wall thickness (in)
4. Δ change in specific term
5. $\in$ strain (in/in)
6. γ ratio of specific heat at constant pressure to specific heat at constant volume
7. τ transmission coefficient of pressure
8. ρ density (lbm/ft^3)
9. ρ_g gas density (lbm/ft^3)
10. ν Poisson's ratio

1 INTRODUCTION

1.1 Purpose

The United States Nuclear Regulatory Commission (NRC) Generic Letter (GL) 96-06 [1] identified potential issues with cooling water systems following either a Loss of Coolant Accident (LOCA) or a Main Steam Line Break (MSLB) concurrent with a Loss of Offsite Power (LOOP). The potential for the effects of waterhammer during the postulated event to damage the system was included in the Generic Letter. Generic Letter 96-06 (GL96-06) was issued following the issuance of LER 1-96-005 [2] and Westinghouse NSAL-96-003 [3], each of which identified similar potential safety issues. Subsequent to the issuance of the Generic Letter and receipt of utility initial submittals, Request for Additional Information letters (RAIs) were sent to many utilities to clarify technical details about their response.

The components of primary interest are the containment air coolers and associated piping. The containment coolers are generally referred to as the containment fan coolers (CFCs), fan cooler units (FCUs), or reactor building cooling units (RBCUs). These components will be referred to generically as fan cooler units or FCUs in this report. The systems that contain the FCUs are referred to as the component cooling water (CCW) or service water (SW) systems. In this report, the system will be referred to as the service water (SW) system but will apply to either system.

During a postulated LOCA (or MSLB) with a concurrent LOOP, the pumps that supply cooling water to the FCUs and the fans that supply air to the FCUs will temporarily lose power. The cooling water flow will lose pressure and stop. The high temperature steam in the containment atmosphere will pass over the FCU tubing with no forced cooling water flowing through the tubing. Boiling may occur in the FCU tubes causing steam bubbles to form in the FCUs and pass into the attached piping creating steam voids. Prior to pump restart, the presence of steam and subcooled water creates 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 closes. The hydrodynamic loads introduced by such a waterhammer event could challenge the integrity and function of the fan cooler units and associated cooling water system, as well as pose a challenge to containment integrity.

The User's Manual (Volume 1) and this Technical Basis Report (TBR) (Volume 2) provide guidance for the evaluation of potential waterhammer events resulting from postulated concurrent LOOP/LOCA or LOOP/MSLB scenarios. These reports are not intended to replace individual plant analyses, but to provide a methodology that can be used to evaluate the potential effects of waterhammer arising from the conditions described in GL96-06. This Technical Basis Report (TBR) supports the User's Manual (UM) provided as Volume 1. The UM recommends methods to be used for the evaluation of the service water system. The TBR presents test data, theory and background information intended to justify the methodology and inputs provided in the User's Manual.

1.2 Scope

The scope of the User's Manual and Technical Basis Report are limited to waterhammer events in the containment cooling systems due to combined LOOP/LOCA or LOOP/MSLB events. The information contained herein may be useful for evaluation of column closure and condensation induced waterhammers in other plant systems, but any discussions regarding these other potential applications are not included in the scope of this report.

Generic Letter 96-06 requested an assessment of three issues. The issues identified in the Generic Letter are as follows:

> "...the stagnant component cooling water in the containment air coolers may boil and create a substantial steam volume in the component cooling water system. As the component cooling water pumps restart, the pumped liquid may rapidly condense this steam volume and produce a water-hammer. The hydrodynamic loads introduced by such a waterhammer event could be substantial, challenging the integrity and function of the containment air coolers and the associated component cooling water system, as well as posing a challenge to containment integrity."
>
> "Cooling water systems serving the containment air coolers may experience two-phase flow conditions during postulated LOCA and MSLB scenarios. The heat removal assumptions for design-basis accident scenarios were based on single-phase flow conditions. Corrective actions may be needed to satisfy system design and operability requirements."
>
> "Thermally induced overpressurization of isolated water-filled piping sections in containment could jeopardize the ability of accident-mitigating systems to perform their safety functions and could lead to a breach of containment integrity via bypass leakage. Corrective actions may be needed to satisfy system operability requirements."

Only the first of these three issues, that issue related to waterhammer occurrence, is included in the scope of this report.

1.3 Risk Considerations

Risk to plant safety is an important consideration in the development and recommended application of the waterhammer modeling approach described in the User's Manual document and justified in this accompanying Technical Basis Report. The probability of the combined initiating events (LOOP/LOCA or LOOP/MSLB) is very low. Waterhammers that could result from these combined events will not lead to pipe failure due to internal pressure since the waterhammer pressures are well below pipe burst pressure. Therefore, the waterhammer loading of concern from the LOOP/LOCA event results primarily from the unbalanced forces produced by traveling pressure waves in the piping system.

An engineering approach to determine waterhammer loading on the piping and support system is presented. This methodology takes advantage of system characteristics such as low system pressure and dissolved non-condensables. The overall solution provides a very high assurance that the pressure boundary of the piping and components inside containment will meet plant design basis requirements. The approach is consistent with the low probability of the initiating events.

1.4 Project Technical Scope

The overall objective of the project is to first understand the behavior of the system during the postulated waterhammer events. The LOOP/LOCA or LOOP/MSLB transients have features that cause the resulting waterhammers to be different from waterhammers described in other documents, such as NUREG/CR-5220 [4]. With an understanding of realistic behavior, a methodology to assure pressure boundary integrity is required. The focus will be on the qualification of the piping supports to assure that the unbalanced forces in the piping are acceptable. The objective is to minimize modifications to plant systems. Adding supports or strengthening existing supports to an existing piping system, if not necessary, will not increase overall plant safety. The analysis methods provide a high degree of assurance that system integrity will be maintained.

The project scope was developed with consideration of the issues raised in Generic Letter 96-06 and the Request for Additional Information (RAI). The project scope was reviewed against the results of the Phenomena Identification and Ranking Table (PIRT) to assure that all important phenomena that needed to be included were in fact included. Specific project tasks were developed to address the phenomena identified to be important.

This report is divided into twelve sections. Each section is referred to in the UM and is intended to be stand-alone. The TBR sections address:

- System and Event Description
- Risk Based Perspective of the Event
- Development of the Technical Approach and Scope
- Plant Waterhammer Experience
- Air Release
- Condensation Induced Waterhammer
- Method of Characteristics for Column Closure Waterhammer Analysis
- Rigid Body Model for Column Closure Waterhammer Analysis
- Column Closure Waterhammer Testing
- Response for LOOP Event versus LOOP/LOCA Event
- Pulse Propagation
- Structural Loading Analysis

The User's Manual and the Technical Basis Report were reviewed by the Nuclear Regulatory Commission. Questions were asked relative to the material provided and answers were provided. Copies of the letters that were provided to the NRC are included in appendix A.

2
EVENT AND SYSTEM DESCRIPTION

2.1 Description of a Typical Fan Cooler System

The fan cooler systems include pumps, piping, fan cooler units, and other in-line components such as valves and orifices. The systems are categorized as either open loop or closed loop systems. Open loop systems are typically found at fresh water sites. Closed loop systems are typically found at salt-water sites.

A diagram of an open loop containment fan cooler system is shown in Figure 2-1. The open loop system features several service water pumps which take suction from the ultimate heat sink and provide flow to the FCUs and other cooling loads. The "ultimate heat sink" is usually a lake, river, or cooling tower. Flow is controlled on the discharge side of the FCU by flow control valves or orifices. The FCUs are often situated at a relatively high elevation in the containment.

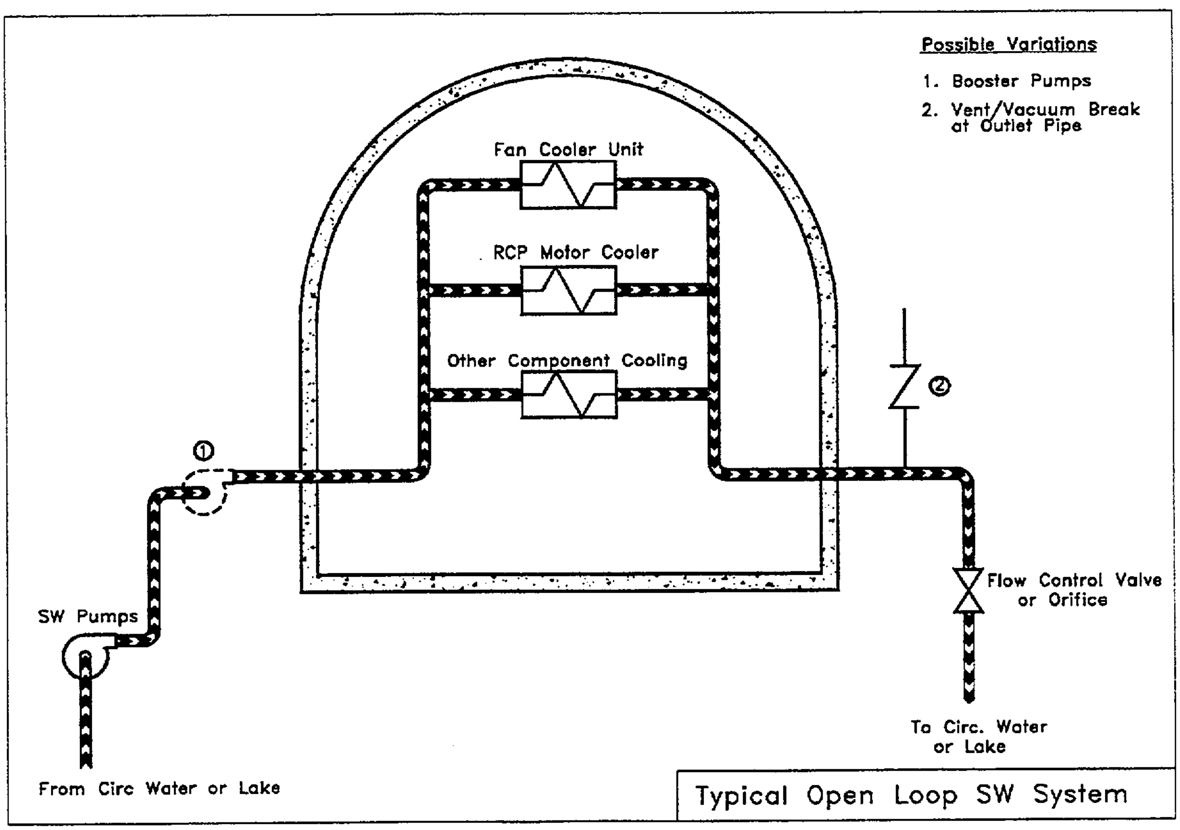


Figure 2-1
Typical Open Loop System

Variations in the open loop configuration that can exist on a plant-to-plant basis include the following:

- Additional auxiliary cooler units can be placed at higher elevations in the containment.
- Some SW systems utilize booster pumps to provide increased pressure to pump cooling water to the FCUs.
- Some SW systems feature a loop seal arrangement near the FCUs to prevent FCU drainage during a loss of pump pressure. Other FCUs can fully drain.
- Some systems feature an outside containment vent/vacuum breaker that will open when the pressure drops below atmospheric.
- The details of the drainage path vary from plant to plant. Long horizontal lines going around the containment exist at some plants. Some units drain constantly in the down direction while others have "loop seals" that are created by the piping going to a higher elevation.
- Pipe diameter varies from 2" to 16" and the thickness varies from schedule 10 to schedule 80.

A typical closed loop containment fan cooler system is shown schematically in Figure 2-2. The typical closed loop system differs from the open loop system in that the service water pumps feed a system that recirculates the water. A heat exchanger removes heat from the cooling loop. A flow control valve or orifice is used to control the flow rate. The system may remain pressurized and full of water when the pumps stop because of a head tank positioned above the height of the FCUs. The head tank also provides a volume expansion capability to accommodate temperature changes in the system.

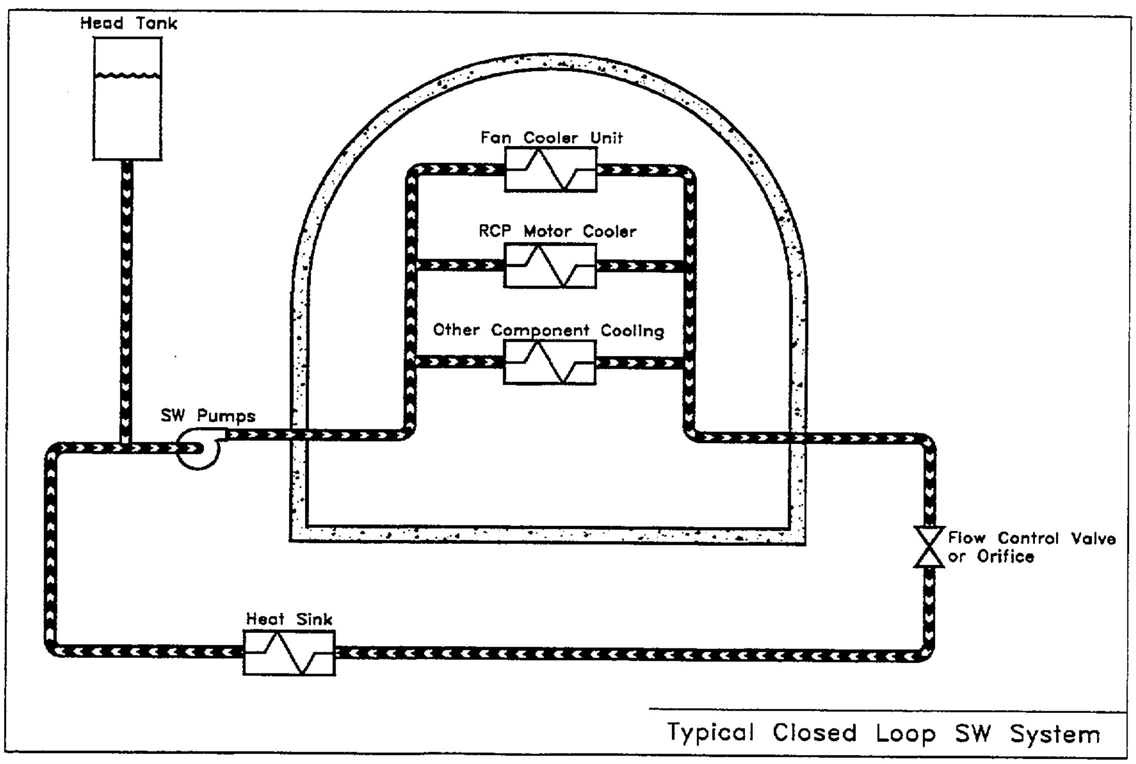


Figure 2-2
Typical Closed Loop System

Most FCUs are designed with sets of multi-pass finned tubes. Containment air is forced over the tubes by fans. The FCUs normally contain multiple banks of coolers. One design is shown in Figure 2-3. Some designs feature supply and return piping that is attached at a low elevation relative to the FCU, allowing it to drain during the transient. Others have a loop seal arrangement that is configured to keep a volume of water in the FCU.

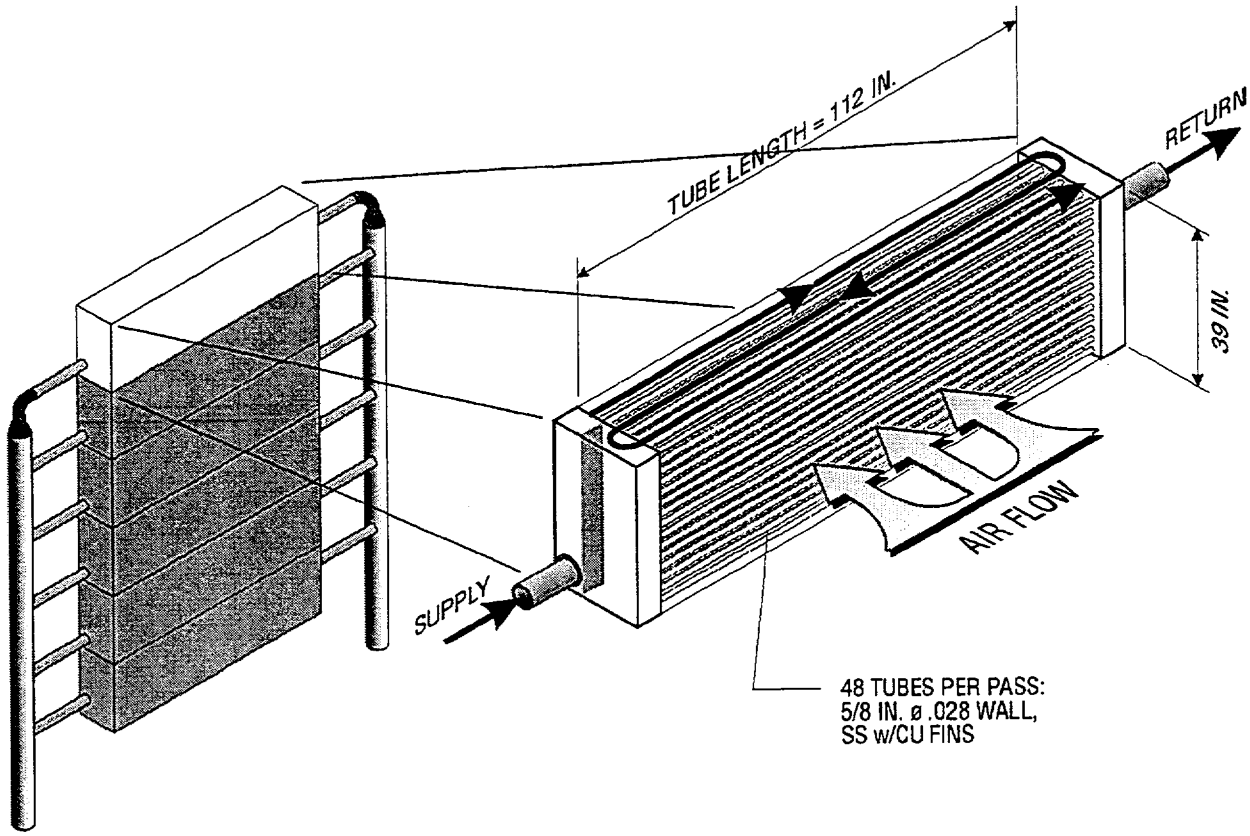


Figure 2-3
Typical Fan Cooler Design

The safety functions generally performed by the FCU system are to:

- remove heat after an accident
- provide cooling to safety related heat loads
- provide a containment pressure boundary

A non-safety related function is to provide containment temperature control during normal operation.

2.2 Postulated Event Description (LOCA/LOOP or MSLB/LOOP)

This section describes the postulated event and describes its influence on the typical fan cooler system.

In both the LOCA and MSLB accident scenarios, steam from the ruptured pipe fills the containment and the temperature inside the containment rises. Examples of LOCA and MSLB containment curves are shown in Figure 2-4 and Figure 2-5. Plant specific curves should be used in individual plant evaluations. At the same time that the LOCA or MSLB occurs, all power is assumed to be lost to the Service Water (SW) pumps and fans in the FCUs. Heat is transferred to the water in the FCUs and boiling occurs. The specific plant evaluations should consider both LOCA and MSLB and include the effects of air in the containment, superheat, and other fluid conditions important to the heat transfer in the fan cooler. The FCUs are generally at high elevations in the containment. Voids will form in piping as a result of column separation in open loop plants and as a result of boiling in the FCUs in both open and closed loop plants.

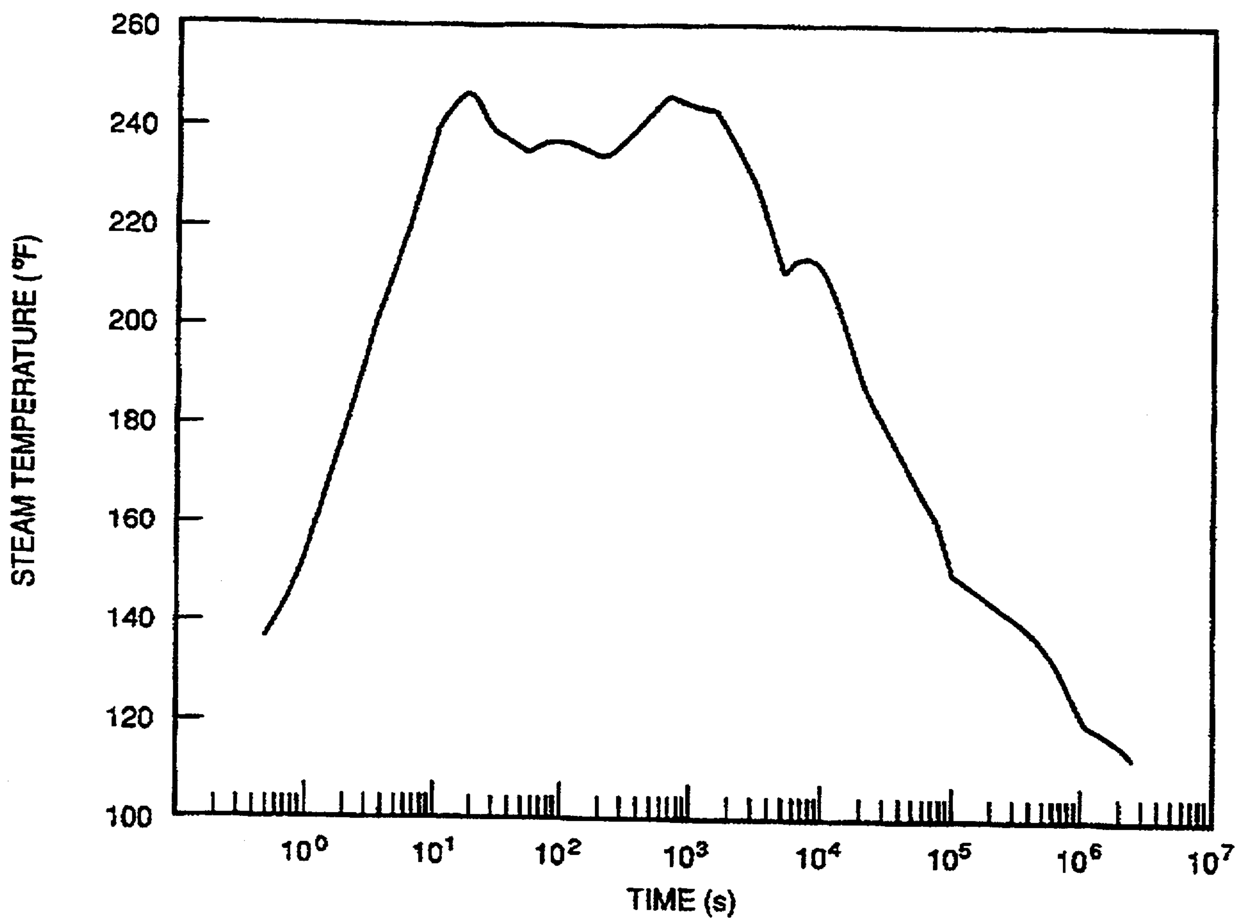


Figure 2-4
Example LOCA Temperature Plot

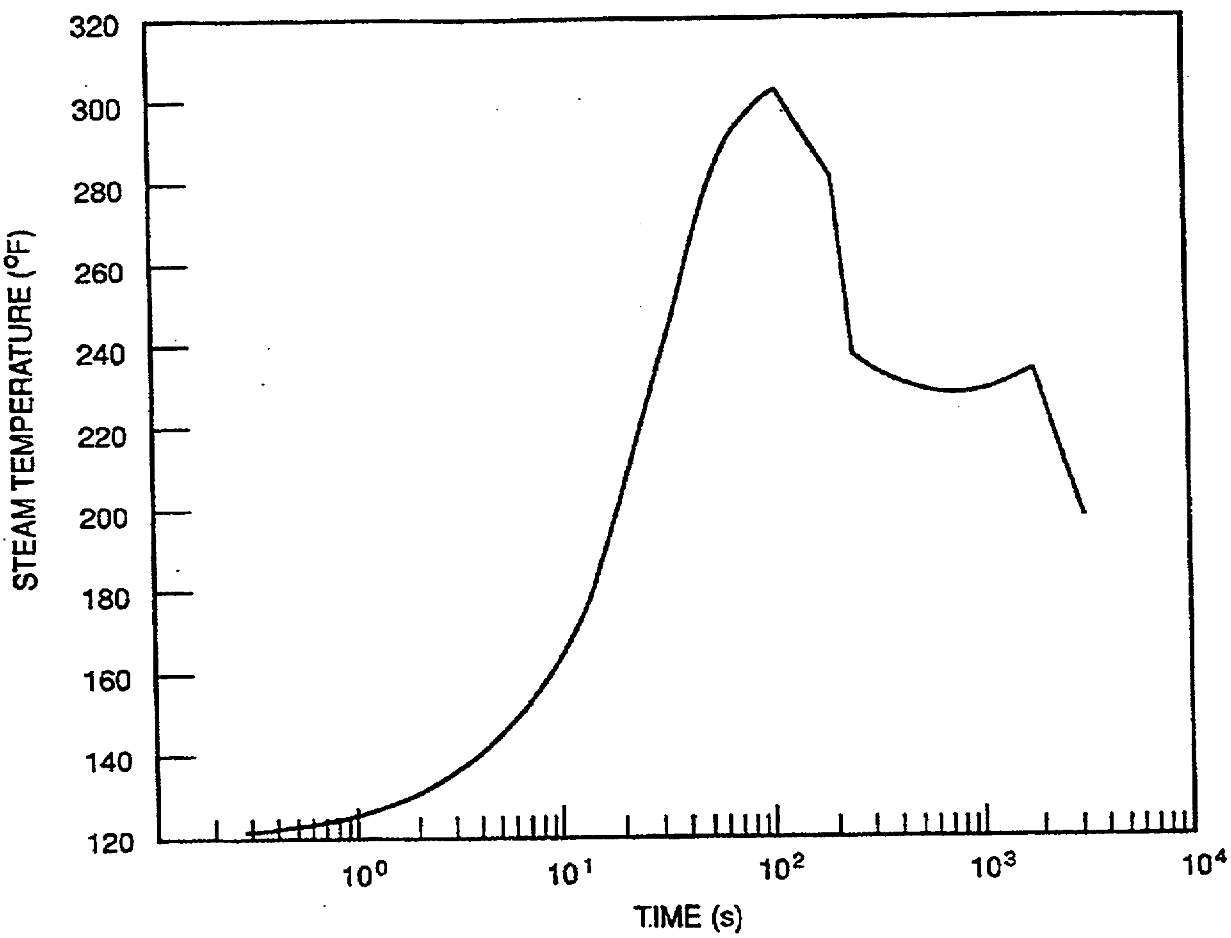


Figure 2-5
Example MSLB Temperature Plot

In an open loop plant, a void may initially form because of gravity drainage due to elevation differences. The voids may expand as a result of pressurization because of steam generation in the FCUs. Boiling is facilitated by the pressure at the FCUs dropping below atmospheric pressure as gravity drainage occurs. Voids may form on both the supply side and the discharge side of the FCUs, although in some plants, the supply side will not drain because of a check valve at the pump discharge. Many plants have a sufficient number of flow paths parallel to the FCUs to permit void formation in both supply and discharge side piping.

In closed loop plants, heat transfer into the FCUs and the subsequent steam formation is required to create voids. Boiling in the fan cooler tubes will initiate later than in an open loop plant because the pressure at the fan coolers will be higher as a result of the water level in the head tank. The loss of pump pressure will reduce the operating system pressure and the boiling point, but due to the absence of gravity drainage, voiding will be limited. The length of the resulting void is highly dependent on many plant-specific system parameters, but the void is generally smaller than in an open loop plant.

Power is restored in approximately 30 seconds from the time that the LOOP occurred. The SW pumps restart and the voided piping will begin to refill. The water column will be accelerated by the pump to a flow rate that is based on the characteristics of the pump and the hydraulic losses in each flow path. The water will progress into the fan coolers and the cold water will stop the boiling and the generation of steam. Eventually, the void will be closed and normal flow will be restored in the fan cooler system.

2.3 LOOP Event

The LOOP event without LOCA or MSLB is an occasional event in most plants. The conditions of the event can be intentionally created in station black-out testing or other periods when pumped flow through the FCUs is not maintained. The primary difference between the LOOP/LOCA or MSLB and the LOOP alone event is the lack of heat transfer throughout the FCUs to the SW during the transient.

In a closed loop plant, most systems utilize a head tank to maintain system pressure. Without the addition of heat from a LOCA or MSLB, the system is unlikely to void due to a LOOP alone event. Without voiding, no waterhammers will occur.

In an open loop plant, the system may void due to the drop in pressure and elevation differences between the heat sink at a low elevation and the FCUs that are often high in containment. The extent of voiding is dependent on plant geometry. Once pump power is restored, the void will close in a similar fashion to that in a LOOP/LOCA or LOOP/MSLB case.

3
RISK PERSPECTIVE

Waterhammer events are postulated to occur in containment fan cooler units (FCUs) if a LOCA (large or medium) or main steam line break (MSLB) inside containment occurs followed by an independent loss of offsite power (LOOP). The LOCAs and steam line break are the only transients that provide the heat input into containment that can result in overheating in the FCUs. It is useful to calculate the frequency of the combination of events to understand the safety significance of the waterhammer. The impact of the occurrence of the LOOP and LOCA or MSLB is dependent on the specific plant configuration but is known to include boiling in the FCU, voiding of part of the service water piping near the FCU, potential waterhammers during the voiding phase, and waterhammer following pump restart and closure of the void. It is the intent of the analyses performed for these post-LOOP/LOCA or MSLB events to demonstrate with a high degree of certainty that the waterhammer events that are postulated to occur would not burst the FCUs or the pipe leading to or from them. Failure of these parts of the service cooling water system, following a LOCA or MSLB will typically result in an increase in the potential for core damage and a large early release.

3.1 Frequency of the Combined Events

The following analysis, based on information for a typical plant Individual Plant Examination (IPE), evaluates the safety significance of the LOCA/MSLB, concurrent with a loss of offsite power. For the purposes of this evaluation, it is assumed that a loss of offsite power within the first 24 hours following the LOCA or steam line break will result in a waterhammer event, even though the period of susceptibility is much less. This is very conservative, since a calculation based on the postulated "concurrent" events approach would yield an infinitely small probability of occurrence.

Representative frequencies for LOCAs (large and medium) and MSLBs inside containment, obtained from a typical IPE are as follows:

- Large LOCA (> 6 inches) = $2.0 \cdot 10^{-4}$/yr.
- Medium LOCA (2 to 6 inches) = $4.6 \cdot 10^{-4}$/yr.
- MSLB Inside Containment = $4.6 \cdot 10^{-4}$/yr.

The probability of loss of offsite power during a 24-hour period following the LOCAs or MSLB, obtained from the same IPE, is $4.1 \cdot 10^{-4}$.

Thus, the frequency of a LOCA/MSLB and loss of offsite power is:

- For Large LOCA, $2.0 \cdot 10^{-4} \times 4.1 \cdot 10^{-4} = 8.2 \cdot 10^{-8}$/yr.
- For Medium LOCA, $4.6 \cdot 10^{-4} \times 4.1 \cdot 10^{-4} = 1.9 \cdot 10^{-7}$/yr.
- For MSLB, $4.6 \cdot 10^{-4} \times 4.1 \cdot 10^{-4} = 1.9 \cdot 10^{-7}$/yr.

The total frequency of these events is: $8.2 \cdot 10^{-8} + 1.9 \cdot 10^{-7} + 1.9 \cdot 10^{-7} = 4.6 \cdot 10^{-7}$/yr.

A survey of operating nuclear plants in the EPRI program was performed to determine the probability of a combined LOOP/LOCA or LOOP/MSLB event. The plants are listed in the following table with the frequency of the initiating event. In one case noted, the evaluation was performed for a LOOP occurring within one minute of the LOCA; all others were for a LOOP within 24 hours of the LOCA. Also noted are frequencies for large ("LG") pipe breaks and for all size pipe breaks ("ALL").

Table 3-1
Plant Combined Event Frequencies (Per Year Unless Noted)

	LOCA/LOOP	LOOP/MSLB
Plant 1	$6.9 \cdot 10^{-7}$	$2.6 \cdot 10^{-9}$
Plant 2	$4.5 \cdot 10^{-7}$	$4.5 \cdot 10^{-9}$
Plant 3	$2.5 \cdot 10^{-9}$ LG ($4.74 \cdot 10^{-8}$ ALL)	$1.7 \cdot 10^{-10}$ LG ($3.3 \cdot 10^{-9}$ ALL)
Plant 4	$2.8 \cdot 10^{-9}$ LG ($7.2 \cdot 10^{-8}$ ALL)	$1.8 \cdot 10^{-10}$ LG ($4.6 \cdot 10^{-9}$ ALL)
Plant 5	$3.0 \cdot 10^{-13}$ (within 1 min)	$1.1 \cdot 10^{-10}$ (within 1 min)
Plant 6	$6.9 \cdot 10^{-7}$	$2.6 \cdot 10^{-7}$
Plant 7	$8.9 \cdot 10^{-8}$	Not provided
Plant 8	$5.8 \cdot 10^{-6}$	$4.7 \cdot 10^{-7}$
Plant 9	$1.4 \cdot 10^{-6}$	$3.1 \cdot 10^{-7}$

As shown above, a typical annual frequency for the waterhammer event caused by all LOCA and MSLB followed by a loss of offsite power is in the order of $5 \cdot 10^{-7}$/yr.

In order to determine the risk significance of FCU system waterhammer events following this unlikely initiator, it is combined with the conditional probability of core damage and with the conditional probability of large early release to yield a core damage frequency (CDF) and large early release frequency (LERF) respectively. The conditional probability of core damage includes three factors: the likelihood of the subsequent waterhammer event, the likelihood that the waterhammer defeats the functionality of the FCU system, and the probability of core damage given the functional loss of the FCU system. It is assumed that waterhammers will occur and that, if the FCU system is not functional, core damage could result. However, it can be shown mechanistically that waterhammer is unlikely to defeat the functionality of the FCU system. For the conditional probability of large early release, there is one additional factor: the probability of large early release given core damage.

According to EPRI and NRC risk significance guidance, this event is of low safety significance, even if it is assumed that waterhammer occurs and results in core damage and large early release (see for example Reg. Guide 1.174 [5]). The section below investigates the likelihood of occurrence for such a waterhammer event.

3.2 Frequency of Failure of the FCU or Piping

Failure is defined as the inability of a component or system to perform its safety function. For the purpose of this evaluation, "breach of the pressure boundary" is the failure of a pipe or other pressure retaining component that is required to maintain system integrity. To achieve pressure boundary integrity, two failure mechanisms should be evaluated for the effects of waterhammer loads. These are the capability of the pipe to withstand the overpressure spike produced by the waterhammer event and the capability of the pipe and supports to withstand the dynamic effects induced by the travelling shock wave. The straight overpressurization has the potential to cause a "burst" type of failure. The travelling shock wave will induce bending in the pipe that could lead to a "peak stress" type of failure.

Pipe Overpressurization

Significant margin exists in the capacity of pipes to withstand pressures greater than the design pressure of the system. The ASME B&PV Code Section III provides margin between material allowables and the design pressure. The calculated burst pressure for a typical carbon steel pipe (A106 Grade B) and copper tube (B280) is provided below:

Table 3-2
Material Allowables and Burst Pressures

Material	P_D (psi)	S_{allow} (ksi)	S_{ult} (ksi)	$OD \times \delta$ (in)	$P_{burst} = \frac{S_{ult} \cdot \delta}{ID/2}$ (psi)	CCWH Pressure at 20 ft/sec (psi)
Pipe - A106 Gr. B	150	15	60	12.75 × 0.375	3,750	600
Tube - B280	150	6	30	5/8 × 0.035	3,780	600

The burst capacities of both the carbon steel pipe and copper tube are significantly greater than predicted peak pressure generated by column closure waterhammer with a velocity as high as 20 ft/sec with no cushioning credited. This velocity exceeds the velocity expected in all plants.

Failure of the pressure boundary due to overpressure is not expected.

Dynamic Effects from Wave Propagation

Structural response predictions of a piping system caused by short duration pressure spikes are almost universally performed using elastic time history analysis methodology or an equivalent elastic static method. These methodologies over-predict the pipe stress and support loads. Typically, energy absorption that occurs in the piping and support systems is not considered in the analysis. Given the short duration of the waterhammers anticipated following a LOOP/LOCA event and the capacity of the supports to absorb energy, a waterhammer would not be expected to cause damage to supports, but even if a support yielded or deformed, energy would be absorbed and that would be beneficial. Extensive support failure and significant subsequent deformation of the pipe would be required in order to challenge the pressure boundary integrity of the pipe. The assurance of qualification of the supporting structures by test or analysis needs to be the focus of the evaluation following a LOOP/LOCA event. It is the only credible manner in which the pressure boundary could be challenged. If qualification is demonstrated, it is very unlikely that a piping system integrity failure could occur.

Support Damage

The design criteria for piping supports in most power plants is based on the stress produced by an equivalent static load. Dynamic loads, like those from waterhammers, are converted into equivalent static loads with much more energy applied than is available in the actual application of the load. Plant experience provides evidence that significant support damage will not occur in supports based on such design criteria. Table 3-3 is derived from Table 5-2 of NUREG/CR-5220 [4] and shows five failed pipe supports in a BWR Residual Heat Removal (RHR) system following a waterhammer event. The dynamic loads and rated capacity of the failed supports is provided, and a factor of safety was determined from the ratio of the load to the rated capacity. It is concluded that margin exists in either the design limits or the method of applying dynamic loads, or both.

Table 3-3
Pipe Support Design Margin for Waterhammer Loading

Support Number	Pipe Size (in)	Pressure Pulse Load (lbs.)	Rated Capacity (lbs.)	Factor of Safety
RH40-1551S	1	3532	1500	2.35
RH40-1544S	3	20959	6000	3.49
RH40-1543S	3	20408	6000	3.40
RH40-1539S	3	20382	6000	3.40
RH40-1554S	10	41697	15000	2.78

3.3 Summary

The program that is reported in the User's Manual and TBR was designed to diminish the use of excessive conservatism. In the development of the program, risk-significance was considered to emphasize realism and gauge the appropriate level of conservatism.

The NRC Probabilistic Risk Assessment (PRA) Policy Statement notes that PRA and associated analyses can be used "to reduce unnecessary conservatism associated with current regulatory requirements, regulatory guides, license commitments, and staff practices."

Simultaneous LOCA and loss of offsite power is a design basis combination of events. Section 3.1 shows that the combination has an extremely low likelihood of occurrence – on the order of $5 \cdot 10^{-7}$/yr. It also states that any resulting CDF or LERF from a subsequent waterhammer is incredibly low. Section 3.2 addresses the possibility of failure of the FCU or piping due to waterhammer pressure pulses or structural loads on pipe supports. Neither would be expected due to a LOOP/LOCA or LOOP/MSLB event.

4
TECHNICAL APPROACH AND SCOPE

4.1 Plan Development Process

The initial project plans were developed with and reviewed by the Waterhammer Expert Panel. The Waterhammer Expert Panel was comprised of Professor Peter Griffith of MIT, Professor Ben Wylie of University of Michigan, and Dr. Fred Moody, formerly of General Electric, and now an independent consultant. The adequacy of the program was further verified by performing a "Phenomena Identification and Ranking Table" (PIRT) assessment.

The PIRT identified the relative importance of the components and phenomena that controlled the occurrence of and plant response to a waterhammer due to voiding and refilling in both open and closed loop systems. A similar ranking process was used so that the critical components and phenomena could be identified.

The PIRT broadly considered the phenomena and defined the phenomena that were the most important to the resolution of the GL96-06 issues. The process reviewed the technical program that was initially identified against the most highly ranked phenomena to determine whether the plan was adequate to provide a high degree of confidence that the methods prescribed would assure the adequacy of the system.

4.1.1 Objective

The overall objective of this project is to first define the realistic behavior of the system as waterhammers occur, and then define appropriate bases for assessing the waterhammers. The PIRT was performed to assess the ability to *realistically* determine the effects of the waterhammer events that would follow the postulated events. The PIRT ranks the components and phenomena from a view of their importance to the overall behavior of the system. The ranking that is performed represents the ability to predict the realistic occurrence and effects of a waterhammer. The rankings are not an assessment of whether it is known how to be conservative, but if it is known how to be accurately and confidently realistic.

Emphasizing the scope and objective of the assessment is important as a starting point for the PIRT. The following scope statement is intended to address the concerns described in GL96-06:

> Waterhammer events may occur in containment cooling systems following the postulated simultaneous occurrence of a LOOP/LOCA or LOOP/MSLB events. The structural integrity of components and structures associated with the containment cooling systems may be challenged as a result of these waterhammer(s). The waterhammer loads should not unacceptably affect the structural integrity of the components and structures associated with the containment cooling system.

4.1.2 Implementation

The PIRT process was implemented through meetings with the Expert Panel, the consultants selected for the project, and utility engineers. Changes to the draft PIRT were noted at these meetings. The PIRT was edited and circulated for comment between meetings. Particular meetings held to develop these evaluations included the following:

April 23, 1999 – First draft of the PIRT developed.

May 5, 1999 – PIRT meeting held to review draft PIRT

June 15, 1999 – PIRT meeting held to review draft PIRT

Brief biographies of the Waterhammer Expert Panel members Professor Peter Griffith of MIT, Professor Ben Wylie of University of Michigan, and Dr. Fred Moody, formerly of General Electric and now an independent consultant follow:

P. Griffith

Peter Griffith is a retired professor of Mechanical Engineering from Massachusetts Institute of Technology (MIT). He received his B. S. in Mechanical Engineering from New York University in 1950, his M. S. in Mechanical Engineering from the University of Michigan, and his Sc.D. from MIT in 1956. He taught at MIT until 1997. He has consulted on thermal hydraulics and nuclear safety for a wide variety of companies, including Westinghouse, General Electric, Babcock and Wilcox, and a variety of other nuclear component suppliers. He has also consulted for a variety of government agencies including the NRC, Department of Energy, and several national laboratories including Oak Ridge, Argonne, Los Alamos, the Idaho National Engineering Laboratory, and Brookhaven. He served on the original PIRT panel for the LBLOCA that ultimately led to a relaxing of the Appendix K licensing requirements. He also served on the SBLOCA PIRT Panel, the AP600 SBLOCA PIRT Panel, and the Direct Containment Heating PIRT Panel. He is the author or co-author of about 100 papers in heat transfer, two-phase flow, and reactor safety.

E. B. Wylie

E. Benjamin Wylie, Professor Emeritus University of Michigan, is a world renowned expert on fluid mechanics and hydraulic transients. He received his B. S. in Civil Engineering from the University of Denver in 1953, his M. S. in Civil Engineering from the University of Colorado in 1955, and his Ph.D. in Hydraulics from the University of Michigan in 1964. He has been a Registered Professional Civil Engineer in Michigan since 1969. He worked briefly as an Assistant Engineer for the City of Englewood, Colorado, a Junior Research Officer in the Hydraulics Section of NRC, Ottawa, Canada, a Structural Design Engineer at Food Motor Co. of Canada, and an Assistant Professor of Civil Engineering at the University of Denver. Dr. Wylie became Assistant Professor at the University of Michigan in 1965. He progressed to Professor in 1970 and Chairman, Department of Civil Engineering in 1984. In 1991 he was named Chairman, Department of Civil & Environmental Engineering from 1991 to 1994. In 1999 he was named Professor Emeritus. Recent consulting work has included EPRI, Akron Brass, Wooster, Ohio, and Naval Undersea Warfare Center, Rhode Island. Dr. Wylie has prepared and presented many technical papers on hydraulics, fluid transients, and system effects. With Professor Emeritus Victor L. Streeter, Dr. Wylie has written several major textbooks including: *Fluid Mechanics*, *Fluid Transients*, and *Fluid Transients in Systems* [6].

F. J. Moody

Fredrick J. Moody is a leading expert in the field of Mechanical Engineering as it pertains to the thermo-dynamics of nuclear containment. He received his B. S. in Mechanical Engineering at the University of Colorado, Boulder in 1958, and he attained his M. S. and Ph.D. degrees in Mechanical Engineering at Stanford University in 1965 and 1970, respectively. Dr. Moody has devoted his career to the design and analysis of boiling water nuclear reactors and containments while working at General Electric Nuclear Energy Co. since 1958, and recently as an independent consultant. For over 30 years, he had been a company-sponsored advanced engineering program instructor and an adjunct professor of thermo-sciences at San Jose State University. Among his major contributions, Dr. Moody developed analytical tools for predicting two-phase liquid/vapor mixture discharge rates from pipe ruptures in high-pressure systems and forces associated with thermal-hydraulic transient phenomena. His works include 50 professional journal articles, 20 presentations at engineering conferences, and a text/reference book entitled, *Introduction to Unsteady Thermofluid Mechanics* [7].

4.2 PIRT Development for Waterhammer in Service Water Systems

The goal of this PIRT is to identify the important processes that can lead to potentially damaging waterhammers in the service water systems of nuclear power plants. The product of this PIRT is a checklist of processes ranked according to their importance – *H*igh, *M*edium, and *L*ow. This checklist was used to help determine whether the evaluation methods used to analyze the thermal hydraulic transients of concern are adequate. In particular, these methods are intended to capture the important fluid hydraulic behavior, yet not be so conservative that unnecessary modifications are required in the piping systems. The checklist was also used to assure that the work performed in preparation for this TBR was complete. The mechanisms and processes that were important to the occurrence and magnitude of the waterhammers were identified and, to the extent that additional information was needed to assess the mechanism or process, the item was added to the work plan.

Waterhammers may occur in service water systems and other plant piping systems during other non-LOOP/LOCA and LOOP/MSLB events or operating modes. These other waterhammers and other events are not the focus of this work. Only waterhammers that uniquely occur as a result of a loss of offsite power (LOOP) alone or a LOOP combined with a LOCA or MSLB will be considered. A part of the PIRT assessment will be to assure that all waterhammers that may occur are identified. Waterhammers that might occur but are expected to be insignificant and those that are not expected to occur will be identified.

It is essential that the analytical methods used to design and evaluate the service water systems during any transient be able to model the thermo-hydraulic processes well enough so that the service water system operability can be determined. The analytical methods will be used to determine the following five thermal hydraulic characteristics needed to determine if a given piping system would remain operable after the transient. These are:

- Peak waterhammer pressure.
- Duration of the pressure pulse.
- Rise time or maximum time derivative of the pressure.
- Characteristic of the acoustic wave transmittal in the piping system.
- Loads in the piping systems and supports.

All these quantities depend, in part, on the characteristics of the piping system in which these thermo-hydraulic processes occur. "Analytical methods" are the method of calculating these quantities for any piping system of interest. The thermo-hydraulic models, analysis methods, computer codes, and piping system models are needed to determine the acceptability of the piping system. All are the "analytical methods."

4.2.1 PIRT

The transient will be divided into two phases for the purposes of the PIRT assessment. The first will be the voiding phase and the second is the refilling phase. The "voiding" phase will be the time that voids are forming in the pipe. This phase will exist from the time that the LOCA or MSLB and the LOOP occur until power is restored to the service water pumps. The "refilling" phase will be from the restoration of power until normal steady state flow is restored in the system. The relation between the PIRT phases and the event time-line with approximate times is presented below.

Table 4-1
PIRT Time Line

Approx. Time (seconds)	Time Line Event	PIRT Phase
0	Concurrent LOOP and LOCA or LOOP and MSLB events	Beginning of the Voiding Phase
5	Pumps and Fans coast down	Voiding
10	FCUs boil and void formation occurs	Voiding
30	Pumps restart	Beginning of the Refilling Phase
37	Water column rejoins closing the void	Refilling

During the voiding phase, depending on the specific system parameters, it is possible that condensation induced waterhammers will occur in horizontal pipes. At the end of the refilling phase, it is likely that a column closure waterhammer will occur. The extent of the void that is likely to form will depend on the heat transfer in the FCU which is difficult to precisely calculate. However, the column closure waterhammer is relatively independent of the precise size of the void and an upper limit on the void size will suffice to bound the answers.

The ranking will follow the guidelines provided below. The second sentence of the ranking definition refers to usage relative to analysis method development and assessment.

- **High** - Phenomena have a dominant impact on the primary parameter of interest. Phenomena should be explicitly and accurately modeled.
- **Medium** - Phenomena have a moderate influence on the primary parameter of interest. Phenomena should be well modeled, but the accuracy need not be as great as for a "high" importance phenomena.
- **Low** - Phenomena have a small effect on the primary parameter of interest. Phenomena may or may not have to be explicitly included in the model. If included, the modeling need not be extremely accurate.

The system and transient will be evaluated both at the component and the process level. If an important process, relative to a specified component, occurs in an unimportant component, the ranking will reflect the combined importance of the two considerations.

It is anticipated that any phenomena ranked "H" in the final ranking will be explicitly included in the program and the analytical methods utilized. For a phenomenon or process ranked "M," a calculation, parametric study, or experimental data may suffice to reduce its importance.

The identification of the phenomena and the ranking process was performed interactively and progressively with the Expert Panel.

4.2.2 PIRT Results

The specific tables representing the voiding and refilling phases are presented in Section 4.3. Notes explaining the ranking are also provided. The items that have a final ranking of "High" are tabulated in Table 4-2 and Table 4-3. These are the items that must be explicitly included in the program in order for the phenomena to be appropriately considered.

The results of the PIRT indicate that two waterhammer types are of concern. These are:

- Condensation induced waterhammers (CIWH) that can occur during the voiding of horizontal pipes, and
- Column closure waterhammers (CCWH) that can occur when the trapped void is collapsed. This generally occurs at the end of refilling for the transient of interest.

Table 4-2
PIRT (Voiding Phase): Components and Phenomena Ranked "High"

Component	Phenomenon Process
Piping	Orientation Elevation Heat Capacity – Pipe Heat Capacity – Water Drainage Flow Regime Gas Accumulation CIWH - Horizontal Pipe CIWH - Loop Seal CIWH - Closed End Branches Steam Void Pressure

Table 4-3
PIRT (Refilling Phase): Components and Phenomena Ranked "High"

Component	Phenomenon Process
Pump (s)	Head Curve
Piping	Orientation Diameter System Geometry Heat Capacity – Pipe Gas Accumulation and Distribution CCWH – Closed End CCWH - Final Closure
Control Valve	Direct Impact if voided

The PIRT also indicated that most of the other components and phenomena that were ranked high were related to the occurrence or magnitude of the CIWH or CCWH. These included such items as orientation of piping, gas in the void, and steam void pressure for the CIWH. Items such as closing velocity (head curve), flow regime, and gas accumulation in the void are ranked high for the CCWH.

Table 4-4 describes the project scope development for the voiding phase of these waterhammer transients, and Table 4-5 describes the project scope development for the refilling phase of these transients.

Table 4-4
Project Scope Development – Voiding Phase

Phenomena Ranked High	Project Activity
CIWH - Pipe Orientation - Elevation - Heat Capacity – Pipe - Heat Capacity – Water - Drainage Flow Regime - Gas Accumulation - Horizontal Pipe - Loop Seal - Steam Void Pressure	Perform tests to define the condensation induced waterhammer magnitude and duration during the voiding phase. The behavior of the free surface and the support reaction loads will be determined. The testing will simulate fan cooler unit (FCU) conditions including steaming rates, draining rates, non-condensable content, pressures, and temperatures. The testing will be performed using 4" piping. The appropriateness of scaling the results of test results to larger pipe diameters will be provided.
Closed End Branches	Closed end branches are not explicitly included. They are identified as an item that requires assessment if they exist at a particular plant site.

Table 4-5
Project Scope Development - Refilling Phase

Phenomena Ranked High	Project Activity
CCWH	Summarize data obtained from plant experience with column closure waterhammer in the service water system following a LOOP. General conclusions from the tests will be provided.
Head Curve Orientation System Geometry Heat Capacity – Pipe Gas Accumulation and Distribution Final Closure	Perform prototypical tests of column closure waterhammer to simulate the conditions experienced in the plant. Prepare an analytical model to predict the column closure waterhammer pressure. The analysis will be correlated and validated to the test results.
Closed End Branches	Closed end branches are not explicitly included. They are identified as an item that requires assessment if they exist at a particular plant site.
Diameter	Methods for defining the appropriate system behavior in plant configurations will be defined from the validated analytical model.
Pressure Wave Propagation	Define method to be used to obtain piping segment forces and to attenuate the pressure wave as the wave travels through the piping.
Support Load Margin	Demonstrate the margin between support loads classically calculated and the loads determined from the testing.

4.3 PIRT for Waterhammer in Service Water Systems

Table 4-6
PIRT for Voiding Phase

Component	Component Ranking	Phenomenon Process	Process Ranking	Overall Ranking
Pump(s)	L	Coast down curve	L	L
Check Valve	L	Valve slam	L	L
Piping	H	Orientation	H	H
		Roughness	L	L
		System Geometry	M	M
		Elevation	H	H
		Diameter	M	M
		Liquid Distribution	M	M
		Heat Capacity – Pipe	H	H
		Heat Capacity – Water	H	H
		Draining Flow Regime	H	H
		Draining Flow Rate	M	M
		Internal Heat Transfer	M	M
		External Heat Transfer	L	L
		Air Accumulation	H	H
		CIWH		
		Horizontal Pipe	H	H
		Loop Seal	H	H
		Vertical Pipe	L	L
		Closed End Branches	H	H
		Initial Temperature	L	L
		Carryover Temperature	L	L
		Pressure Wave Amplification due to Fluid Structure Interaction	L	L
		Pressure Wave Amplification due to Area Changes	M	M
		Pressure wave attenuation	M	M
		Steam/Non-condensables Distribution	M	M
		Steam Void Pressure	H	H
Fittings	L	Resistance to Flow	L	L
		Initial Temperature	L	L
FCU	M	Fan Coast Down	M	M
		Heat Transfer Coefficient	M	M
		Inventory/Dryout	M	M
		Heat Capacity	L	L
		Flow Resistance	L	L
		Preheated Draining Water	M	M
		CIWH	L	L
		Pressure Wave Attenuation	L	L
Control Valve or Orifice	M	Flow Resistance	M	M
		Transmission/Reflection	L	L
		Flashing Velocity Change	L	L

Table 4-7
PIRT for Refilling Phase

Component	Component Ranking	Phenomenon Process	Process Ranking	Overall Ranking
Pump(s)	H	Head Curve	H	H
		Restart Time	L	L
Check Valve	L	Valve Slam	L	L
Piping	H	Orientation	H	H
		Roughness	L	L
		System Geometry	H	H
		Elevation	L	L
		Diameter	H	H
		Liquid Distribution	L	L
		Heat capacity – Pipe	H	H
		Heat capacity – Water	M	M
		Flow Regime	M	M
		Internal Heat Transfer	M	M
		External Heat Transfer	L	L
		Air Accumulation and Distribution	H	H
		CIWH		
		Horizontal Pipe	L	L
		Loop Seal	L	L
		Vertical Pipe	M	M
		Closed End Branches	M	M
		CCWH		
		Loop Seal	M	M
		Closed End	H	H
		Final Closure	H	H
		Thermal Layer	M	M
		Pressure Wave Amplification due to Fluid Structure Interaction	L	L
		Pressure Wave Amplification due to Area Changes	M	M
		Pressure Wave Attenuation	M	M
		Steam Void Pressure	M	M
Fittings	L	Resistance to Flow	M	L
		Impacts during Refilling	L	L
		Initial Temperature	L	L
Automated Valves	L	Closure	L	L
FCU	M	Filling Pattern	M	M
		Flow Resistance	M	M
		Heat Transfer Coefficient	M	M
		Pressure Wave Attenuation	M	M
		Heat Capacity	L	L
		Final Inventory	M	M
		CIWH	L	L
		CCWH	L	L
Control Valve	H	Flow Resistance	M	M
		Direct Impact if voided	H	H
		Transmission/Reflection	L	L
		Flashing Velocity Change	L	L

4.4 Discussion of PIRT for Voiding Phase

4.4.1 Pumps

Drainage Phase

The pumps are not very important to waterhammer creation during the drain-down phase since they quickly coast down and stop pumping fluid.

Component Ranking - L

Phenomena for Pumps	Remarks	Process Ranking
Pump Coast Down	The pumps will lose power with the LOOP and coast down until stopped. Variability in the speed of this coast down will affect the drain-down rate, but, as long as the system will be voided, this phenomenon will be relatively unimportant compared to the parameters which cause condensation induced waterhammer (CIWH).	L

4.4.2 Check Valve

Some plants utilize a check valve at the pump discharge. This valve has the potential to affect drain-down rates and to produce a waterhammer when the flow reverses.

Component Ranking – L

Phenomena for Check Valve	Remarks	Process Ranking
Valve Slam	The check valve may rapidly close as the pump stops and flow may reverse, producing a waterhammer proportional to the velocity of the reversing flow. This phenomenon is unlikely to be important to the loading of the system for several reasons. First, the velocity of the reversing flow will be driven by gravity only and is unlikely to be large. Second, most cooling water systems have multiple flow paths from a common header. The flow returning from the higher elevation coolers will have alternate paths through which to drain; therefore, the flow reversing velocity through the check valve will be further reduced.	L

4.4.3 Piping

The piping providing supply and return flow to the Fan Cooler Units (FCUs) affects the magnitude of waterhammer loads and is directly impacted by waterhammer loads that occur during the transient.

Component Ranking – H

Phenomena for Piping	Remarks	Process Ranking
Diameter	The pipe diameter will primarily influence the potential to create CIWH and also influence system resistance and drain-down rate.	M
Orientation	The orientation of the piping will play a critical role in the potential waterhammers that may occur during the drain-down. Horizontal pipes of sufficient length may experience CIWH. Vertical pipes draining down are not likely to experience waterhammer problems.	H
System Geometry	The overall system geometry includes lengths of pipe, intersections, changes in direction, etc. The geometry has a moderate effect on the creation of waterhammer and loading of the pipe system.	M
Elevation	The pipe elevation will influence the local pressure in the pipe and influence void creation as the system drains. The elevation will also influence the system drain-down rate.	H
Liquid Distribution	The void will have to progress into horizontal pipe sections in order to produce the potential for condensation induced waterhammer. Beyond this void size, additional extent is relatively unimportant. The distribution of liquid can possibly form multiple voids but each should behave in a similar manner.	M
Pipe Heat Capacity	The heat capacity of the FCU piping will provide a heat sink for condensation of the steam produced in the FCUs. The amount condensed will affect the pressure of the steam void, the amount of non-condensables that accumulate, and therefore the magnitude of the condensation induced waterhammers. See also the discussion of fan cooler heat transfer capability.	H
Water Heat Capacity	The heat capacity of the water in the FCU piping will also provide a heat sink for condensation of the steam produced in the FCUs. The amount condensed will affect the pressure of the steam void, the amount of non-condensables that accumulate, and therefore the magnitude of the condensation induced waterhammers. See also the discussion of fan cooler heat transfer capability.	H
Draining Flow Regime	The draining flow regime is important in horizontal pipes since it describes the method by which the pipe clears of fluid. The pipe can drain in one of two ways. The pipe can drain in a stratified manner that allows steam to pass over the draining water and possibly trap steam bubbles causing waterhammer. Alternatively, the water/steam interface can pass axially down the length of the horizontal run without the potential to trap steam bubbles. Testing has shown that both draining regimes can produce waterhammer. Therefore, the draining regime is important to condensation induced waterhammer creation and pipe loading.	H
Draining Flow Rate	The draining flow rate is important in horizontal pipes since it influences the flow regime as described above. Therefore, the draining rate is important to condensation induced waterhammer creation and pipe loading.	M

Phenomena for Piping	Remarks	Process Ranking
Internal Heat Transfer/ Condensation	The horizontal pipe supplying to and returning from the FCUs will initially be cooler than the steam produced by boiling in the FCUs. As the water in the supply pipe drains and is exposed to the FCU steam, the steam will condense on the pipe inside surface. Steam will also condense on the exposed water surfaces. This becomes important as large surfaces are exposed, particularly when draining through horizontal pipe. This process will be important to the pressure of the steam void and will therefore contribute to the magnitude of the CIWH.	M
External Heat Transfer	The horizontal pipe supplying to and returning from the FCUs will be exposed to the containment environment and experience heating from the surrounding steam. Many plants have insulation on this pipe. Even without insulation, the time constant for the heating of the pipe from outside heat transfer is longer than the approximately 35 second duration of the event. External heating will negligibly affect waterhammer or pipe loading.	L
Air Accumulation	As condensation occurs in the piping, non-condensables mixed with the steam will be left behind and entrained at the draining water interface, appearing as small bubbles. These bubbles will influence waterhammer primarily because the sonic velocity in the water will be reduced, lowering waterhammer magnitude. Therefore, air in the fluid will reduce waterhammer magnitude and lower piping loads.	H
CIWH – Horizontal Pipe	Draining condensation induced waterhammers are likely for length to diameter ratios $L/D > 24$.	H
CIWH – Loop Seal	CIWH in horizontal pipe may be influenced by elevated sections downstream that change the draining characteristics. The loop seal assessment includes vertical pipe draining upward.	H
CIWH – Vertical Pipe	Vertical pipe draining down is unlikely to experience CIWH.	L
CIWH – Closed End Branches	CIWH produced from voids collapsing against a closed end may provide a higher pressure pulse (doubled) than voids collapsing against standing water.	H
Initial Temperature	The initial temperature of the service water or closed cooling water is typically in a relatively narrow range and is much lower than the containment temperature following a LOCA or MSLB event, which will transfer large amounts of heat to this fluid. Variation within the expected operating range is insignificant to the event.	L
Carryover Temperature	The temperature of liquid carryover is not significant as the heat capacity of the carryover liquid is so small compared to the other heat capacities in the problem.	L

Phenomena for Piping	Remarks	Process Ranking
Pressure Wave Amplification due to Fluid Structure Interaction	Pressure wave amplification due to fluid structural interaction (FSI) is unlikely to affect the magnitude of a waterhammer pressure wave by more than several percent. For a single wave travelling through a piping system, the primary FSI generated pressure pulse starts at the opposite end of a pipe segment as a waterhammer pressure wave. This, in effect, lowers the net differential pressure and reduces pipe loading. Although multiple waves can be formed to act in an additive manner, this scenario is unlikely to be significant relative to the main pressure pulse loading of the system. The uncertainties in the loading force calculation overwhelm this possible effect.	L
Pressure Wave Amplification due to Area Changes	Pressure waves change magnitude as they enter pipe sections of different cross sectional area. Increasing area attenuates pressure pulses and decreasing area can magnify a pulse. However, the pipe loading is based on the pressure times the area, which tends to reduce the load.	M
Pressure Wave Attenuation	Pressure waves can attenuate due to piping friction and the energy lost due to moving the pipe. These losses can reduce the magnitude of the pressure wave traveling through the system. They can be important in limiting the load on the system at moderate and large distances from the source event.	M
Steam/Non-condensables Distribution	Steam and non-condensables distributed throughout the piping system can reduce the sonic velocity and therefore the travelling speed of the pressure pulse. This will influence the pipe loading.	M
Steam Void Pressure	The pressure in the steam void can greatly influence the energy of the condensation induced void closure and therefore the magnitude of the pressure pulse.	H

4.4.4 Fittings

The fittings act in conjunction with the piping and contribute to the overall pressure losses in the piping system. They are generally not important to the occurrence or magnitude of the waterhammer.

Component Ranking – L

Phenomena for Fittings	Remarks	Process Ranking
Resistance to Flow	The flow resistance in each fitting will have a minor influence on draining rate and therefore the extent of voiding.	L
Initial Temperature	The initial temperature of the fittings will be approximately the service water or closed cooling water system temperature. The fitting temperatures will be much less important than the temperature of the piping due to the much smaller fitting area.	L

4.4.5 Fan Cooler Units

The fan cooler units provide the primary heat transfer capability for the system and contribute to the formation of steam voids with the drop in system pressure following a LOOP.

Component Ranking – M

Phenomena for FCUs	Remarks	Process Ranking
Fan Coast Down	Condensation of steam from the steam/air mixture is the most important source of heat in the LOOP/LOCA transient. The fans are important in that they blow the air away and keep the heat transfer rate up. This parameter is perhaps important, but will have to be handled in individual plant analyses.	M
Heat Capacity	The heat capacity of the FCU will affect the "thermal inertia" or the time in which the FCU can respond. Given the design of the FCUs to transfer heat from the containment to the service water , this value is small (the FCUs are good heat transfer devices). Therefore, the FCU heat capacity is insignificant compared to the total amount of heat transferred during the transient.	L
Heat Transfer	The heat transfer rate to the FCU is important in that it will typically be large enough to boil the fluid and create steam voids large enough to progress into the piping system. The rate of steam generation will affect the pressure in the steam void. The steam pressure is determined by the balance of the steam generated, the increase in available volume due to draining, and the amount of condensation on the pipe walls and draining fluid. The steam void pressure should drive CIWH magnitudes. This variable must be handled in individual plant analyses.	M
Inventory / Dryout	The configuration of the FCU may allow the water to either drain or remain wet throughout the transient, depending on the location, top, or bottom, of drains from the FCU. The available inventory of water is important to the ability of the fan cooler to generate steam and therefore create the potential for condensation induced waterhammers.	M
Flow Resistance	The flow resistance of the FCU may impact drain-down rates if elevated piping drains through the FCU during drain-down. This should be a minor effect. Additionally, the net flow area in the FCUs is greater than that of the connecting pipes.	L
Preheated Draining Water	The water draining from the cooler will be heated before steam voids are formed and exit the cooler. This "preheated draining water" will reduce the magnitude of potential waterhammers by influencing steam void pressure.	M
CIWH	Condensation induced waterhammer occurring inside the tubes of a draining fan cooler is unlikely because the tubes and fluid will be heated up to saturation conditions before steam voids are formed. Significant contact between subcooled water ($\Delta T_{sc} > 36°F$) and hot steam are required to produce a waterhammer. Even if a CIWH were to occur, the resulting forces are likely to be insignificant due to the small cross sectional area of each tube and the fact that the waterhammers in individual tubes will be out of phase if, indeed, they occur at all.	L

Pressure Wave Attenuation	Pressure wave attenuation through the complicated geometry of the FCU helps determine which portions of the system are affected by the advancing pressure wave. It is apparent from some test data that pressure waves can pass through the FCUs. However, steam voids in the FCU and in the piping between the FCU and the location of the CIWH will "isolate" the FCU from the traveling pressure waves. This greatly reduces the potential for the FCUs to ever be exposed to CIWH pressure pulses.	L

4.4.6 Control Valve

Most systems use a control valve or an orifice downstream of the FCUs and outside containment to control the pressure drop and therefore flow to the ultimate heat sink. Pressure drop across this device can affect drain-down rates and affect waterhammer occurrence and magnitude.

Component Ranking – M

Phenomena for Control Valve	Remarks	Process Ranking
Flow Resistance	The flow resistance provided by the control valve or orifice will affect the system draining characteristics, therefore affecting the extent and pressure of the steam void and the magnitude of potential CIWHs. This value is fairly well known since it is the main flow control point in the system.	M
Transmission/ Reflection	The outlet control valve or orifice will provide a partial reflection of the pressure wave as it passes through this restriction. This will have a moderate effect on loading of the piping system, but attenuation in the piping is likely to have greatly reduced the pressure wave by the time this part of the system is reached.	L
Flashing/ Velocity Change	The heating of the fluid and the pressure drop across the valve can produce flashing at the valve. Flashing at the outlet control valve or orifice will suddenly restrict flow and produce a waterhammer/fluid transient event. This effect is likely to be small relative to the CIWH or CCWHs expected to occur in the system.	L

4.5 Discussion of PIRT for Refilling Phase

4.5.1 Pumps

The pumps are very important to the system loading as they directly affect the refilling velocity that determines the potential severity of the column closure waterhammer.

Component Ranking – H

Phenomena for Pumps	Remarks	Process Ranking
Pump Head	The pump head will drive the closure velocity for the refilling water, directly contributing to the column closure waterhammer magnitude. The pump head is related to the system resistance by the pump curve.	H
Pump Restart Time	The pumps will restart and rapidly begin to refill the system. Pump start-up speed is much shorter than the time needed to fill the system, so the pumps are expected to be operating at full speed by the time column closure waterhammer (CCWH) occurs. Pump start-up time is therefore relatively unimportant to CCWH.	L

4.5.2 Check Valve

Some plants utilize a check valve at the pump discharge. It has the little potential to affect refilling rates or to produce a waterhammer due to reverse-flow valve slam during refilling.

Component Ranking – L

Phenomena for Check Valves	Remarks	Process Ranking
Valve Slam	The check valve may rapidly close as the pump starts and flow in paths parallel to the pump may reverse, producing a waterhammer proportional to the velocity of the reversing flow. Even if a single failure of the valve is assumed to produce a condition with the valve stuck open, this phenomenon is unlikely to occur since the check valves will be closed at pump restart.	L

4.5.3 Piping

The piping providing supply and return flow to the fan cooler units (FCUs) is directly impacted by hydrodynamic loads during the transient.

Component Ranking – H

Phenomena for Piping	Remarks	Process Ranking
Orientation	The orientation of the piping will play a significant role in the potential waterhammers that may occur during the refilling phase. The pipe will fill under different flow regimes based on the orientation of the pipe and velocity of the fluid.	H

Phenomena for Piping	Remarks	Process Ranking
Roughness	The pipe roughness will contribute to the overall flow resistance and thus influence refilling rate. This will have a small effect on waterhammer magnitude because fitting losses dominate the pressure losses.	L
System Geometry	The overall system geometry used in this PIRT includes lengths of pipe, intersections, changes in direction, diameter, etc., but not elevation changes. The geometry has a strong effect on the creation of column closure waterhammer and loading of the pipe system.	H
Elevation	Since the pump head is greater than elevation head, the pipe elevation will not have a significant influence on the system refill.	L
Diameter	Since the pipe loads are proportional to the pressure times the cross sectional pipe area, the pipe diameter will influence the loads on the system subjected to a CCWH pressure pulse.	H
Liquid Distribution	The distribution of liquid can result in multiple voids but each void should behave in a similar predictable manner. The details of the liquid distribution will not have a significant effect on the WH.	L
Flow Regime	The refilling flow regime is important in horizontal pipes since it describes the method by which the pipe fills with fluid. At high Froude numbers, the refilling pipe will run full and not permit the conditions that can lead to a CIWH. At low Froude numbers, the pipe can fill in a stratified manner that allows steam to pass over the filling water and possibly trap steam bubbles causing waterhammer. Even if a CIWH occurred, it would not be worse than waterhammers during the draining phase as the water temperature will have increased and additional condensation and accumulation of non-condensables will have occurred by this time.	M
Internal Heat Transfer	The internal heat transfer will influence the pressurization of the steam void as it is collapsed by the closing columns. This will influence column closure waterhammer magnitude.	M
External Heat Transfer	The piping supplying to and returning from the FCUs will be exposed to the containment environment and experience heating from the surrounding steam. Many plants have insulation on this pipe. Even without insulation, the time constant for the heating of the pipe from outside heat transfer is longer than the approximately 35-second duration of the event. External heating will negligibly affect waterhammer or pipe loading.	L
Pipe Heat Capacity	The heat capacity of the piping will provide a heat sink for condensation of steam in the void and influence the pressurization of the steam void as it is collapsed by the closing columns. This will influence column closure waterhammer magnitude and the amount of air left behind when the steam is condensed.	H

Phenomena for Piping	Remarks	Process Ranking
Water Heat Capacity	The heat capacity of the water will provide a heat sink for condensation of steam in the void and influence the pressurization of the steam void as it is collapsed by the closing columns. This will influence CCWH magnitude. The heat that is used to raise the temperature of the pipes is more important as a source of air to reduce the WH magnitude than the heat transferred to the water.	M
Air Accumulation and Distribution	As condensation occurs in the piping, non-condensables mixed with the steam will be left behind and entrained at the draining water interface, appearing as small bubbles. These bubbles will influence waterhammer by reducing the local sonic velocity in the water thus, lowering the waterhammer magnitude. Therefore, air in the fluid will reduce waterhammer magnitude and lower piping loads.	H
CIWH – Horizontal Pipe	Refilling CIWHs are possible for length/diameter ratios > 24 if the flow is stratified. Stratified flow is unlikely to occur at the expected refilling velocities as the filling Froude number is greater than one.	L
CIWH – Loop Seal	CIWH in horizontal pipe may be influenced by elevated sections downstream that change the draining characteristics, but at the expected refilling velocities, this is unlikely.	L
CIWH – Vertical Pipe	Vertical pipe filling up is very unlikely to experience CIWH. Vertical pipe filling down can allow waterhammers to occur if the velocity is low. This is unlikely at the expected filling velocities and Froude numbers.	M
CIWH – Closed End Branches	CIWH produced from voids collapsing against a closed end may provide a higher pressure pulse (doubled) than voids collapsing against standing water. The velocity of closure will be limited by the refilling velocity in that branch.	M
CCWH – Loop Seal	CCWH may occur when a stagnant loop of water is impacted by the refilling column. The column length is generally much shorter and the pulse duration should be shorter also.	M
CCWH – Closed End Branches	CCWH produced from a column collapsing against a closed end may provide a higher pressure pulse (doubled) that voids collapsing against standing water.	H
CCWH – Final Closure	The final CCWH produced when the last void in the system is closed will produce the longest continuous water solid section and often the highest velocities. Therefore, the final closure should be the largest and longest duration pulse.	H
Thermal Layer	A thermal layer or section of hot water insulating the steam void from direct contact with refilling subcooled fluid will influence the steam partial pressure in the void and therefore allow some steam pressurization. This will cushion the collapse in a similar manner to air in the void.	M

Phenomena for Piping	Remarks	Process Ranking
Pressure Wave Amplification due to Fluid Structure Interaction	Pressure wave amplification due to fluid structural interaction (FSI) is unlikely to affect the magnitude of a waterhammer pressure wave by more than several percent. For a single wave travelling through a piping system, the primary FSI generated pressure pulse starts at the opposite end of a pipe segment as a waterhammer pressure wave. This, in effect, lowers the net differential pressure and reduces pipe loading. Although multiple waves can be formed to act in an additive manner, this scenario is unlikely to be significant relative to the main pressure pulse loading of the system. The uncertainties in the loading force calculation overwhelm this possible effect.	L
Pressure Wave Amplification due to Area Changes	Pressure waves change magnitude as they enter pipe sections of different cross sectional area. Increasing area attenuates pressure pulses and decreasing area can magnify a pulse. However, the pipe loading is based on the pressure times the area, which tends to reduce the load.	M
Pressure Wave Attenuation	Pressure waves can attenuate due to piping friction and the energy lost due to moving the pipe. These losses can reduce the magnitude of the pressure wave traveling through the system. They are important in limiting the load on the system at moderate and large distances from the source event.	M
Steam Void Pressure	The partial pressure of the steam in the void will influence the column closure velocity and therefore the magnitude of the pressure pulse.	M

4.5.4 Fittings

The fittings act in conjunction with the piping and contribute to the overall pressure losses in the piping system. They are generally not important to the occurrence or magnitude of the waterhammer.

Component Ranking – L

Phenomena for Fittings	Remarks	Process Ranking
Resistance to Flow	The flow resistance in each fitting will have a minor influence on the refilling rate and therefore the column closure velocity.	M
Refilling Impacts	During the system refilling, the mass of refilling water will impact elbows, tees, or other changes in direction. This load will be proportional to the square of the velocity of the refilling water ($F=\rho AV^2/g$). For typical refilling speeds of 10-20 ft/sec, the refilling loads should be much less than the waterhammer pressure pulse loading.	L
Initial Temperature	The initial temperature of the piping will be approximately the service water or closed cooling water system temperature. After exposure to steam from the FCUs, the piping should be well above the initial values. Variations in the initial temperature of the piping will not significantly affect the ability to condense steam.	L

4.5.5 Automated Valves

Automated valves (MOVs, AOVs) that operate during the event may affect the column closure, but are unlikely to operate quickly enough to fully actuate during the event.

Component Ranking – L

Phenomena for Automated Valves	Remarks	Process Ranking
Closure of Valves	Automated valves (MOVs, AOVs) that operate during the event may affect the column closure, but are unlikely to operate quickly enough to fully actuate during the event.	L

4.5.6 Fan Cooler Units

The fan cooler units provide the primary heat transfer capability for the system and contribute to the formation of steam voids with the drop in system pressure following a LOOP.

Component Ranking – M

Phenomena for FCUs	Remarks	Process Ranking
Filling Pattern	The filling pattern of the FCUs is important in that it will potentially create conditions for CCWH to occur. If water can pass through the FCU lower tubes, fill the exit plenum, reverse flow into the upper tubes, and meet the normal filling water in the mid-tube region, there is a potential to cause column closure at higher than the closure velocity for water entering from a single side. However, this is unlikely because the heating as the fluid passes through the tube will provide an insulating thermal layer that will allow steam pressure in the void to limit column closure velocity.	M
Flow Resistance	The flow resistance of the FCU will reduce the refilling velocity and therefore help reduce the magnitude of the CCWH.	M
Heat Transfer Coefficient	The heat transfer rate from the FCU to the water is important during the refilling phase since it will transfer heat to the refilling water and help create an insulating thermal layer. This will help limit CCWH magnitudes.	M
Pressure Wave Attenuation	Pressure wave attenuation through the complicated geometry of the FCU is important in determining the portions of the system affected by the advancing pressure wave. It is apparent from some test data that pressure waves can pass through the FCUs.	M
Heat Capacity	The FCUs heat capacity is relatively unimportant during the refilling phase. It will transfer some heat to the refilling water and help create an insulating thermal layer, helping to limit CCWH magnitudes.	L

Phenomena for FCUs	Remarks	Process Ranking
Final Inventory	The final inventory just before refilling will affect the FCU refilling pattern and provide a volume of preheated water. The potential to drain the FCU completely dry will primarily affect steam void pressure.	M
CIWH	Condensation induced waterhammer occurring inside the tubes of a refilling fan cooler is unlikely because the tubes and fluid will be heated to saturation conditions before steam voids are formed. Significant mixing of subcooled water ($\Delta T_{sc} >$ 36°F) and hot steam are required to produce a waterhammer. The flow velocity through the tubes also will have a Froude number greater than one so that the tubes will not become stratified. Even if a CIWH were to occur, the resulting forces are likely to be insignificant due to the small cross sectional area of each tube and the fact that the CIWHs for individual tubes would be out of phase.	L
CCWH	Column closure can potentially occur in a refilling FCU. However, this is unlikely because the heating as the fluid passes through the tube will provide an insulating thermal layer that will allow steam pressure in the void to limit column closure velocity.	L

4.5.7 Control Valve

Most systems use a control valve or an orifice to control the pressure drop and therefore flow to the ultimate heat sink. The closure velocity can be reduced by the valve or orifice so this device can affect the waterhammer.

Component Ranking – H

Phenomena for Control Valve	Remarks	Process Ranking
Flow Resistance	The flow resistance provided by the outlet control valve or orifice will affect the system flow characteristics, therefore affecting the velocity of the downstream water column and the relative velocity at closure.	M
Direct Impact	If the piping system is voided to the location of the control valve or orifice, the rejoining column may impact directly on the component. This has the potential to double the predicted CCWH magnitude calculated for a water on water rejoin. Most plants do not void to this location.	H
Transmission/ Reflection	The outlet control valve or orifice will provide a partial reflection of the pressure wave as it passes through this restriction. This will have a moderate effect on loading of the piping system, but attenuation in the piping is likely to have greatly reduced the pressure wave by the time this part of the system is reached.	L
Flashing/Velocity Change	The heating of the fluid and the pressure drop across the valve can produce flashing at the valve. Flashing at the outlet control valve or orifice will suddenly restrict flow and produce a waterhammer/fluid transient event. This event is likely to be small relative to the CIWH or CCWHs expected to occur in the system.	L

4.6 Relation to GL96-06 and Requests for Additional Information (RAI)

The relationship between the issues raised in the RAI and the issues described in the TBR have been summarized in Table 4-8. The statement in the RAI has been extracted. A statement of what the TBR has done, and the location in the TBR is included in the table.

Table 4-8
RAI/TBR Comparison

Request for Additional Information	User's Manual and Technical Basis Report	TBR Section
If a methodology other than that discussed in NUREG/CR-5220, "Diagnosis of Condensation Induced Waterhammer," was used in evaluating the effects of waterhammer, describe this alternate methodology in detail. Also, explain why this methodology is applicable and gives conservative results (typically accomplished through rigorous plant-specific modeling, testing, and analysis).	• The UM and TBR provide methods to predict column closure waterhammers.	8, 9, 10
	• The TBR provides test results for the occurrence of condensation induced waterhammer and concludes that it is not the limiting waterhammer.	7
Identify any computer codes that were used in the waterhammer and two-phase flow analyses and describe the methods used to benchmark the codes for the specific loading conditions involved.	• The UM and TBR do not prescribe specific computer codes.	NA
Describe and justify all assumptions and input parameters (including those used in any computer codes) such as amplifications due to fluid structure interaction, cushioning, speed of sound, force reductions, and mesh sizes, and explain why the values selected give conservative results. Also provide justification for omitting any effects that may be relevant to the analysis (e.g. fluid structure interaction, flow induced vibration, and erosion).	• Fluid structure interaction is addressed in the PIRT and in the TBR.	12
	• Cushioning by steam and/or gas is addressed.	8, 9, 10
	• Sonic velocities have been measured and are defined.	7, 10
	• The conservatism in support force calculations is defined.	13
	• Mesh sizes are not specifically addressed in the TBR since the TBR does not prescribe codes.	NA
	• Amplifications due to fluid structure interaction are described and recommendations provided.	12
	• Erosion and flow induced vibration is not a waterhammer issue and is not addressed in the TBR.	NA

Request for Additional Information	User's Manual and Technical Basis Report	TBR Section
Provide a detailed description of the "worst case" scenarios for waterhammer and two-phase flow, taking into consideration the complete range of event possibilities, system configurations, and parameters. For example, all waterhammer types and water slug scenarios should be considered, as well as temperatures, pressures, flow rates, load combinations, and potential component failures. Additional examples include: - the effects of void fraction on flow balance and heat transfer - the consequences of steam formation, transport, and accumulation - cavitation, resonance, and fatigue effects - erosion considerations	• Guidance for defining "worst case" scenarios for waterhammer is provided. This includes the possible component failures and "pre-event" operating modes. • The methods for calculating the waterhammers and pressure pulse characteristics include the effects of pressure, temperature, flow rates, and void fractions. • Load combinations are specified in specific plant FSARs and are not included in the TBR. • Resonance effects are addressed. • Cavitation and erosion are not addressed in the TBR as they are considered two-phase flow piping wear issues.	3, 4 7, 9 NA 12 NA
Confirm that the analyses included a complete failure modes and effects analysis (FMEA) for all components or explain why a complete and fully documented FMEA was not performed.	• Guidance for FMEA is provided.	3, 4
Explain and justify all uses of "engineering judgement".	• The PIRT utilizes the experience of an Expert Panel to assure completeness of issue consideration. • A plant will be able to compare their uses of "engineering judgement" in previous evaluations against the TBR methods/results to justify the conservatism of their approach.	4 4, 5
Determine the uncertainty in the waterhammer and two-phase flow analyses, explain how it was determined, and how it was accounted for to assure conservative results.	• The certainty and uncertainty in the waterhammer evaluation is addressed.	4
Provide a simplified diagram of the affected system, showing major components, active components, relative elevations, lengths of piping runs, and the location of any orifices and flow restrictions.	• The TBR pro vides simplified schematics of typical open loop and closed loop systems. Detailed system diagrams for the specific plants will be supplied by the particular plants.	2, 5

5
PLANT WATERHAMMER EXPERIENCE

Column closure waterhammers have occurred many times in nuclear power plant service water systems. Many of these column closure events are caused by design basis transients and others occur during testing.

5.1 Description of LOOP Waterhammer Occurrences

In open loop plants, voiding can occur in the fan coolers and related piping each time that the service water pumps are shut down. This can occur each time that a LOOP occurs or, more importantly, each time a LOOP test is performed. At many plants, a station blackout test is performed during every refueling outage. Because of the frequency of these events, plant waterhammer experience is important to indicate the impact of the waterhammer following the postulated LOOP.

Tests have been conducted by installing pressure transducers and other instrumentation to monitor system response to LOOP tests. These tests have shown that the impact of waterhammer on the piping and supports is relatively minor. Since the column closure waterhammer following the LOOP with LOCA or MSLB is less severe than the waterhammer caused by a LOOP alone (see Section 11), the limited or negligible effect of "LOOP alone" waterhammers is important. Many of the LOOP testing configurations bound the design basis configuration of the system, and the degree of severity of the loading can be meaningfully assessed by considering plant LOOP experience.

Nine plants have documented the occurrence of column closure waterhammer experience during testing for LOOP. Many other plants recognize the existence of the conditions that would allow a waterhammer to occur during LOOP testing. All the plants were open loop plants. All of the column closure waterhammers occurred during some type of system testing. Conditions prior to or during each test allowed voids to develop in the system. At the end of the refilling of the system, column closure waterhammers occurred. Lack of precise information on measurement locations, data scanning frequencies, and other similar information prevents a detailed analysis of the data.

Six of the nine plants recorded system pressure data during the waterhammer occurrence. In some cases, instrumentation locations and configurations did not allow direct correlation between the measured pressures pulses and the pulse at the point of void closure.

An example of a pressure trace recorded during an actual column closure occurrence is provided in Figure 5-1. Figure 5-1 is an overview of the entire transient, showing pump stop, drain-down, refilling, and an approximately 205-psig peak pressure during column closure.

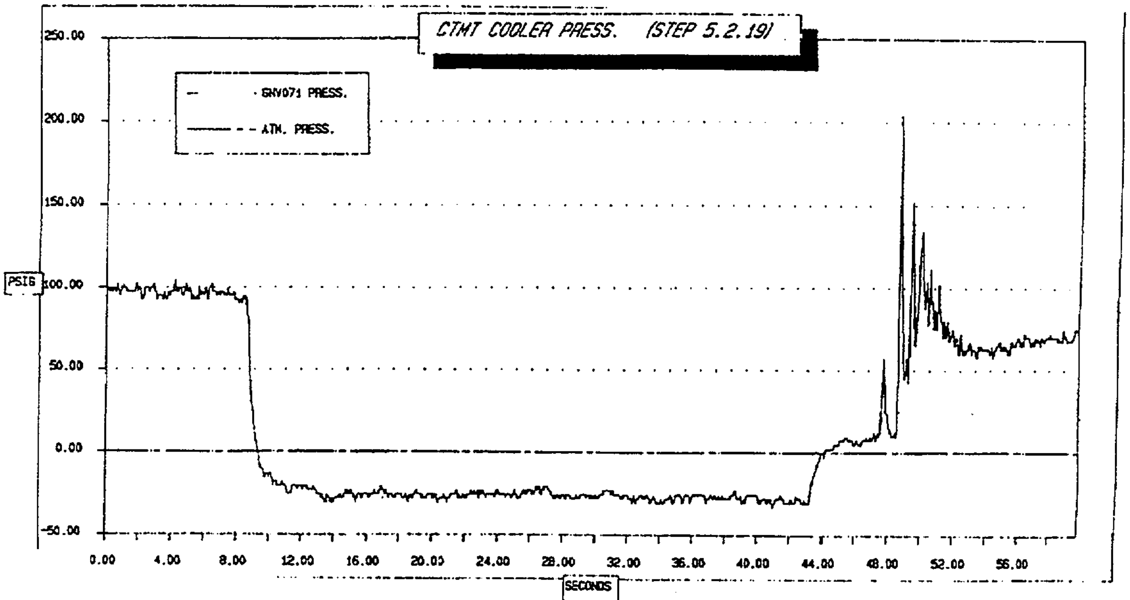


Figure 5-1
LOOP Test

In no case was there any damage noted to the pressure boundary, even following detailed inspection of the pressure boundary. In one instance, there was minor support damage specifically attributed to the column closure waterhammer. In two other instances, minor support damage was noted in the support system that may have been caused by the CCWH.

5.2 Summary of Plant LOOP Experience

Table 5-1 presents a summary of the test data obtained from the nine plants who documented column closure waterhammer during testing.

Table 5-1
Summary of Plant CCWH Test Experience

Plant	Measured Pressure (psig)	Pressure Boundary Damage?	Number of Damaged Supports	Support Damage Type
A	205	No	1	• bent threaded rod • snubber clamp rotation
B	135	No	0	
C	193	No	0	
D	550	No	0	
E	330	No	0	
F	50	No	0	
G	N/A	No	1	• snubber damage
H	N/A	No	0	
I	N/A	No	1	• damage to strut clamp • support movement

Plant A is an open loop system with typical bottom-draining FCUs. These FCUs have an elevation up to 92 ft above the water source, which clearly will separate when the pump flow stops. Figure 5-1 shows a measured peak pressure of 205 psig for Plant A. This closure occurred in 10" schedule 40 piping with an estimated closure impact velocity of 12 ft/sec. Support damage noted is tabulated in Table 5-1.

Plant B is an open loop system with typically top-draining FCUs. These FCUs typically have an elevation of 53 ft above the water source with one at a higher elevation, which clearly will separate when the pump flow stops. Plant B recorded pressure pluses of approximately 80 psi above the operating pressure of approximately 55 psig with an estimated closure impact velocity of 10 ft/sec. Figures 5-2 and 5-3 show the recorded data.

Plant C is an open loop service water system which experiences column separation in control building air-conditioning water coolers. These coolers were approximately 80 ft above the water source, and column separation would have occurred when the pumps stopped. As noted in Table 5-1, a peak pressure of 193 psig was measured when the service water pump was restarted. A design change was made to allow air to break the vacuum on the inlet piping to these coolers. This eliminated the column closure waterhammer when the service water pumps started.

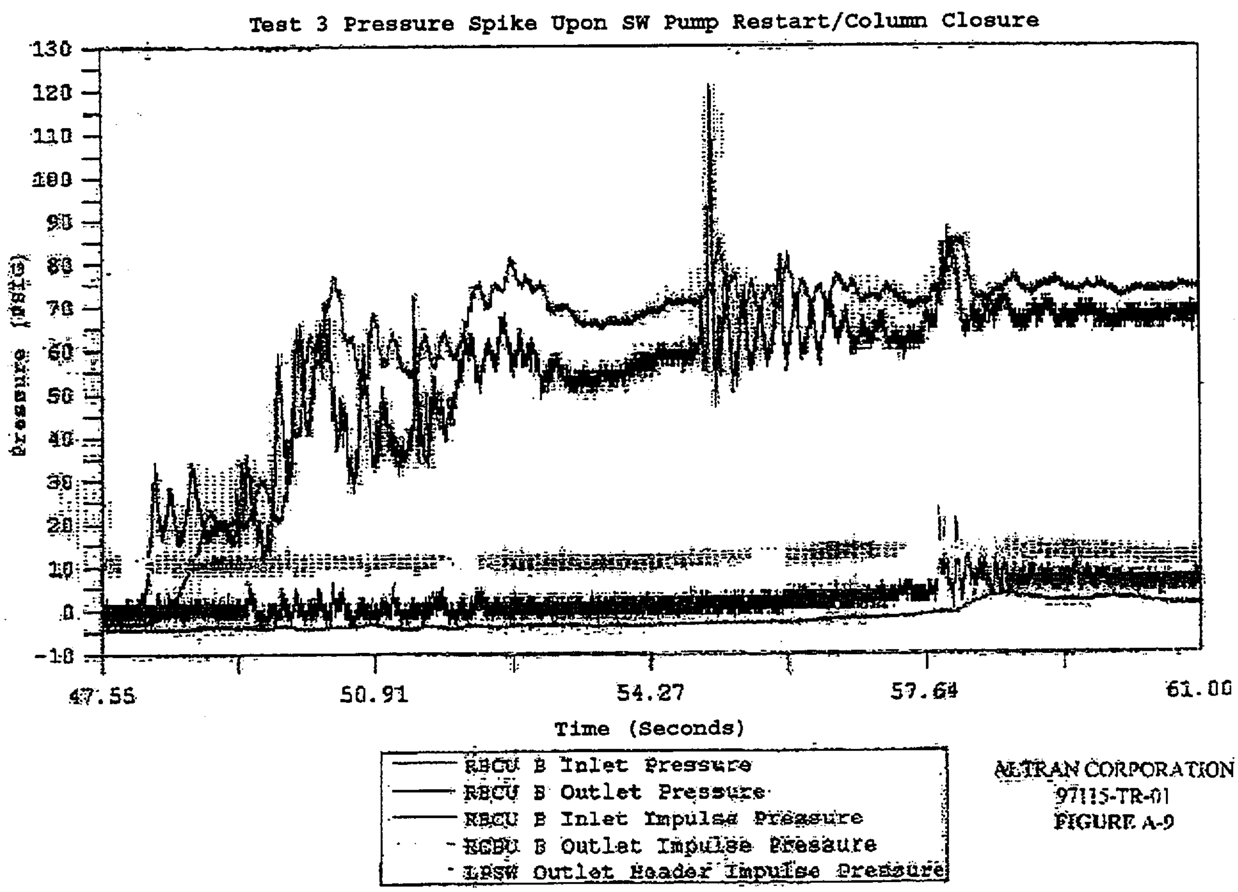


Figure 5-2
Test 3 Pressure Spike Upon SW Pump Restart/Column Closure

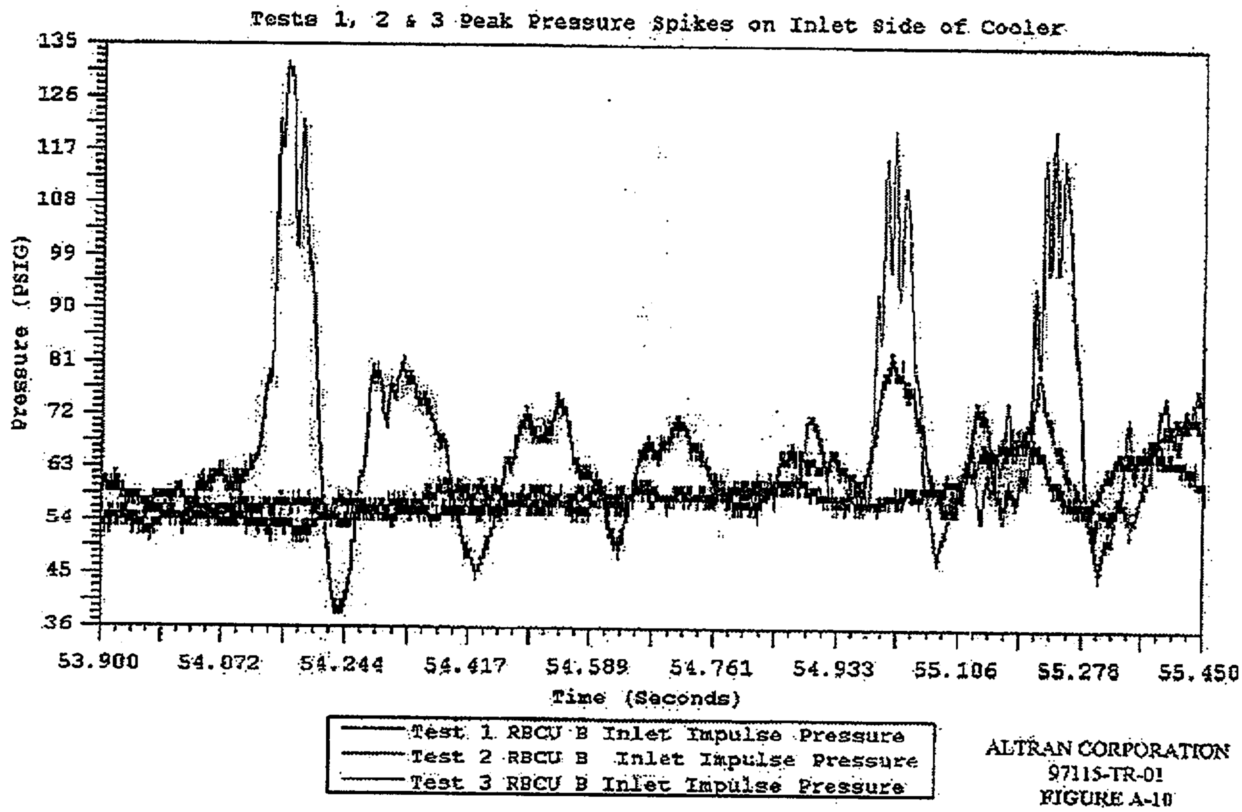


Figure 5-3
Tests 1, 2, and 3 Peak Pressure Spikes on Inlet Side of Cooler

Plant D is an open loop system with typical bottom-draining FCUs. These FCUs have an elevation up to 72 ft above the water source, which clearly will separate when the pump flow stops. Table 5-1 shows a measured peak pressure of 550 psig for Plant D which occurred on the return side of one of the FCUs. One-half-inch pipe deflections were noted during the testing, but no damage was observed following any of the tests.

Plant E is an open loop system with top-draining FCUs. These FCUs have an elevation of 87 ft above the water source which clearly will separate when the pump flow stops. Even though there was a vacuum breaker on the discharge piping from the FCUs, a peak pressure of 330 psig was measured on the inlet piping to an FCU when the pump was restarted. No damage was observed.

Plant F (similar to Plant E) is an open loop system with top-draining FCUs. These FCUs have an elevation of 87 ft above the water source which clearly will separate when the pump flow stops. Plant F also has a vacuum breaker on the discharge piping from the FCUs. A peak pressure of 50 psig was measured on the inlet piping to an FCU when the pump was restarted. No damage was observed.

Plant G experienced column closure waterhammer during startup testing in the FCU supply lines. A pipe support snubber was damaged. The pump restart time delay was set longer and the waterhammer was avoided in future testing.

Plant H experienced column closure waterhammer in lines feeding the pump coolers. Noise was heard and pressure spikes were detected, but no damage was observed. Vacuum breakers were installed and waterhammers were then averted.

Plant I experienced column closure waterhammer during LOOP testing. As noted in Table 5-1, there was damage to a clamp for a pipe strut and three other adjacent pipe supports moved on the piping.

The conclusions from the plant experience investigation are based on both the monitored events described above and the very large number of events that have occurred during normal testing. During testing, many open loop plants will void in the fan cooler and experience a column closure waterhammer following the restart of the pumps. No pressure boundary damage was noted following any of this extensive in-plant testing.

The results indicate that the magnitude of the column closure waterhammers due to LOOP-related events in nuclear power plant service water systems is insufficient to challenge the system pressure boundary. The investigation indicates that support damage may be experienced in very isolated situations as a result of the column closure waterhammer. The support damage that was noted was minor and would not challenge the system's ability to perform its design functions.

6 GAS RELEASE

Dissolved non-condensable gasses released from a raw water system during a combined LOOP/LOCA or LOOP/MSLB event can have two beneficial effects. First, gas can evolve into the steam voids formed due to pressure drop and heat addition. This gas can pressurize during a column closure event and cushion the impact. Second, gas can evolve and remain in the water as small bubbles and reduce sonic velocity. This section provides information on the release of gas that may become available to cushion the final impact of a CCWH.

The amount of dissolved gas in the water stream is plant specific, although water in all open loop and closed loop systems are expected to contain dissolved gas. Open loop plants, in general, have more dissolved gas because the systems draw from water sources at or near the dissolved gas saturation point. Closed loop plants may lose dissolved oxygen due to corrosion processes or corrosion inhibitors. The corrosion inhibitors scavenge oxygen and subsequently the level of dissolved gas is reduced. However, closed loop systems may also have a pressurized nitrogen blanket increasing the amount of dissolved nitrogen in the system.

During the LOCA/LOOP transient the system pressure will drop. For open loop plants, this will likely result in the pressure falling below the gas saturation pressure (the gas saturation pressure may be thought of as the partial pressure of the gas at the surge tank for closed loop plants or at the source of water for open loop plants). In open loop plants, some gas release as a result of a pressure drop alone is expected. For closed loop plants, the gas saturation pressure is normally not reached as a result of the pressure drop alone because the surge tank provides a head of water on the system even after power is lost.

This section presents a basis for predicting the evolution of gas due to both depressurization and low pressure boiling. The depressurization model is not used in the solution steps presented in the User's Manual.

The low pressure boiling gas release was determined by testing. The test is the representation of a heat exchanger single-tube under prototypical low-pressure conditions. The gas removed from this water is used as a basis for determining the gas release from the mass of water in a FCU during a combined LOOP/LOCA.

6.1 Gas Release Due to System Depressurization

In a piping system that loses pump pressure, the local pressure in the system is determined by the relative elevation of the piping and fluid reservoir. If the local fluid pressure drops to the saturation point, vapor voids can form as the system drains. If left depressurized, the system will continue to drain until the piping is voided to an elevation approximately one atmosphere of head (about 33 feet for cold water) above the reservoir level. The pressure above this level will be the saturation pressure for the liquid vapor.

A raw water system that is exposed to this voiding phenomenon will experience evolution of dissolved gases in the water close to the voided region. Raw water is typically saturated with air at atmospheric pressure, and the pressure in the region of the void will approach the saturation point, less than 1 psia for water that is less than 100°F. This presents a significant dissolved gas overpressure for a fluid that was saturated at atmospheric pressure, or in a supersaturation state. The pressure drop, heat transfer leading to steam formation, and water flow cause the dissolved gas to be released, forming tiny bubbles in the liquid.

A prediction of the release of non-condensables from a depressurized liquid is required. Two references present background for determining the amount of released non-condensable gases.

The first is entitled *Gas Evolution in Liquids and Cavitation* and was written by Schweitzer and Szebehely [9]. Their test apparatus consisted of a container partially filled of the test fluid. The container was depressurized and agitated, and the change in pressure in the volume above the liquid was measured. The rate of gas release was related to the change in pressure. The conclusion of this test was that the rate of evolution was proportional to the supersaturation. The expression for the evolved volume of gas as a function of time is provided in Equation 10 of the paper and is as follows:

$$\Delta Vol_g / Vol_L = \frac{S \cdot r}{S + r} \cdot \frac{p_e - p_g}{p_o} \cdot \left(1 - \exp\left(-0.693 \frac{t}{t_E}\right)\right) \qquad 6\text{-}1$$

Detailed descriptions of these terms may be found in Reference [9], but generally they are as follows:

$\Delta Vol_g / Vol_L$ = volume of gas released per liquid volume

S = solubility constant (1.84% was determined for water based on the experimental conditions)

r = gas-liquid volume ratio

p_e = equilibrium or saturation pressure (psia)

p_g = gas pressure above the liquid (psia)

p_o = initial system pressure (psia)

t_E = half life of evolution (3.86 seconds for the experimental conditions)

The solubility constant S and half-life t_E vary between experimental and plant conditions. The testing reported in the paper determined that the half-life t_E was 3.86 seconds. The difference between experimental and the in-plant solubility for the fan cooler depressurization case is generally minor since the testing was performed at room temperature. The difference in half life between the experiments and the in-service conditions may be more significant due to the testing having applied mechanical agitation while the plant condition will have steam formation and fluid flow. However, the Schweitzer and Szebehely paper indicates, "If the pressure drop is produced suddenly, rapid evolution does take place. The liquid surface suffers a break which is equivalent to agitation and immediate bubble formation can be observed." The half-life determined in the experiment is assumed to be reasonable, particularly when compared to the twenty or thirty seconds of sub-atmospheric conditions that exist in most power plant applications. This assumption is also validated by comparison with the second paper described below.

The second reference is entitled *Gas Release in Transient Pipe Flow* and was written by Zielke and Perko [10]. Their test apparatus consisted of a loop of flowing water that was rapidly depressurized. The evolved air bubbles were measured using optical scattered light and acoustical methods. The results of these tests also showed an exponential relationship for the mass of gas released with the supersaturation of the liquid. This is shown in Equation 5 of the referenced paper and is as follows:

$$m_{rate} = k_1 \cdot \frac{p_e - p_g}{p_o} \cdot exp\left(-9.2 \cdot \frac{p_g}{p_e}\right) \cdot Re^{86} \qquad \text{6-2}$$

where

m_{rate} = mass release rate of dissolved gas per m^3 of liquid (kg/s·m^3)

k_1 = constant based on the pipe diameter = $7.1 \cdot 10^{-11}/D^2$ (kg/s·m^3)

Re = Reynolds number

Given enough time, the amount of gas released reaches a maximum value that corresponds to Equation 6 of the referenced paper, reproduced below.

$$m_{max} = k_2 \cdot \frac{(p_e - p_g)^{2.59}}{p_o} \cdot \left(exp\left(-9.3 \cdot \frac{p_g}{p_e}\right)\right) \qquad \text{6-3}$$

where:

m_{max} = maximum free gas concentration reached after the gas release activity phase per m^3 of liquid (kg/s·m^3)

k_2 = constant based on the pipe diameter = $1.8 \cdot 10^{-4}/D$ (kg/m^3)

Calculations for a typical draining raw water system were prepared. The transient results are presented in Figure 6-1. The analyzed cases presented in this figure are described as the base cases for the two models. For these cases, the water is assumed to be saturated at atmospheric pressure and 60°F. The low pressure region of water near the void is 4 psia. This pressure range will conservatively include the water immediately adjacent to the void (1 psia) and all water within approximately 5 vertical feet of the void and water that passes through horizontal lines near the void. The water is assumed to drain at a modest rate of 5 ft/sec through an 8" nominal diameter pipe. It is assumed that the gas liquid volume ratio is very small for full running pipe (r = 0.0001), and this is conservative since a partially voided pipe would evolve much more air.

For a depressurized system, it can be shown that 2 to $3 \cdot 10^{-2}$ g/m^3 (Figure 6-1) of air is released from saturated water during the voiding phase. The conditions providing this amount of gas release were as follows:

- System pressure in void region — 4 psia or less
- Void time — greater than 10 seconds
- Water — air saturated at 14.7 psia (atmospheric pressure)

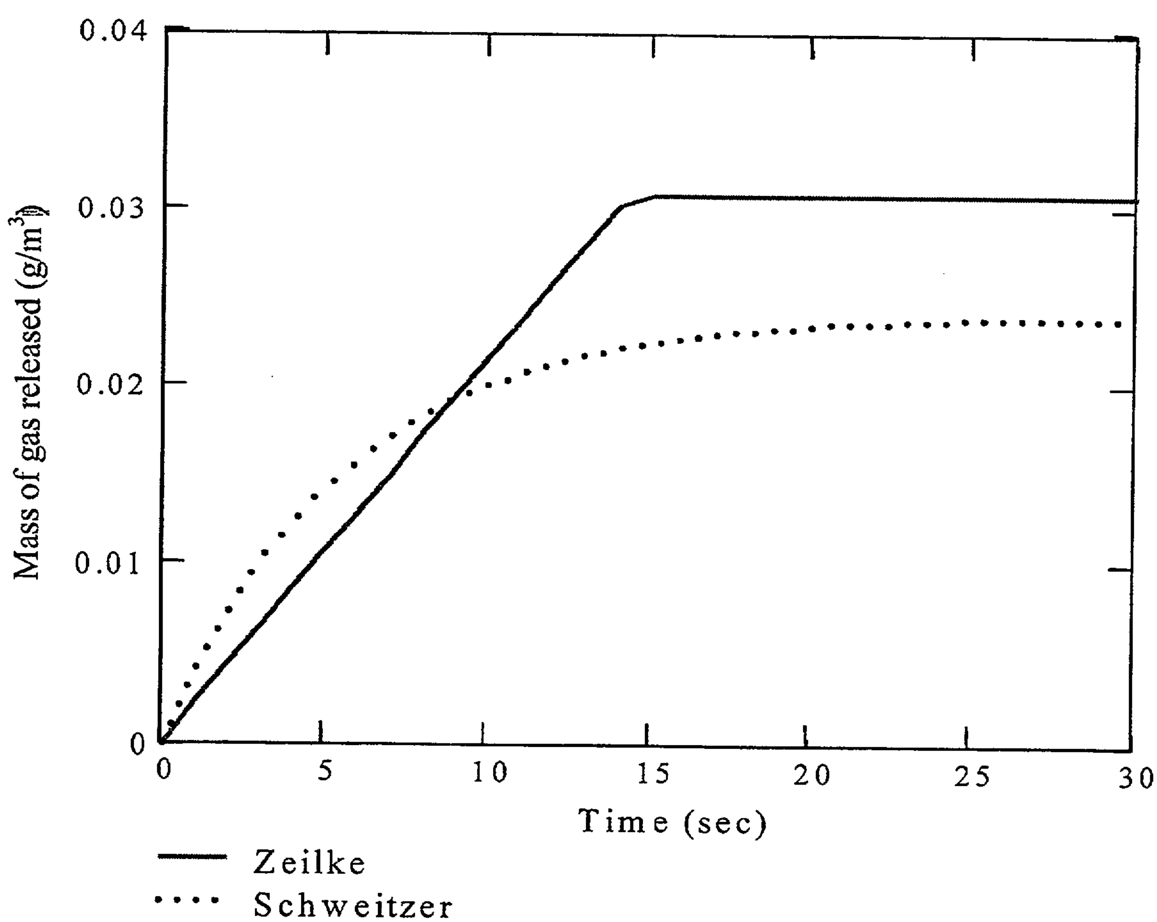


Figure 6-1
Air Release per Schweitzer and Zeilke Models

Figure 6-1 shows that the amount of dissolved gas released due to depressurization alone reaches a maximum value of approximately 0.031 gm/m^3 during the 30 second transient. The testing performed in the development of the data used to create Figure 6-1 was based on an agitated sample of water that was super-saturated with gas. The agitation was caused either by flow of the water through a pipe or through simple shaking. No boiling occurred in these tests.

The tests described in the next section show that water in the heat exchanger tubes, when exposed to boiling, would release approximately 50% of their dissolved non-condensable gas. Based on a total dissolved gas concentration of approximately 20 mg/L or 20 gm/m^3, 50% gas release would evaolve 10 gm/m^3. Therefore, the effect of pressure alone is approximately 0.3% of the mass released by boiling.

6.2 Gas Release Due to Boiling

During the LOCA, the temperature of the water in the FCUs will be increased in both the closed and open loop plants. The temperature rise and pressure drop may result in boiling in the FCUs. Two-phase flow conditions will initiate at the exit of the coolers during the transient because the water near the outlet will have absorbed the most heat. The tubes will void as water is displaced into the downstream piping. The water will release non-condensables as it is exposed to:

- Boiling/Two-Phase Flow
- Increased Temperature
- Pressure Drop

Water that is in the cooler once boiling initiates will have to traverse the remaining length of tubing in a two-phase flow condition. In addition, any water that enters the FCU subsequent to initiation of boiling will experience two-phase flow as it traverses a tube length. Boiling and two-phase flow conditions are efficient means of stripping gas from water.

It is the objective of the testing to determine a conservative amount of gas that will be released in the plant due to boiling in the FCU. An individual plant analysis is required to define the behavior of the FCU, but if boiling occurs, accelerated gas release is expected. A conservative amount of gas that will be released will be defined by performing tests to define the amount of gas that will be released from a given volume of water and then by taking the gas release from a smaller amount of water than is expected to be affected by the transient. For example, gas released from water that enters the FCU during pump coastdown after the beginning of the transient will be ignored. Gas released from water that will re-enter the hot fan cooler once the pumps restart will also be ignored. It is considered likely that much more gas will be released than that determined by the recommendations presented herein.

6.3 Testing

6.3.1 Objective

Testing was performed to determine the percentage of air that would be evolved from water in the FCUs in the time period between loss of power and void closure following pump restart. This was accomplished by measuring the dissolved oxygen content of water before and after boiling for a time period and conditions similar to plant LOOP/LOCA conditions. Dissolved oxygen was used as an indicator of overall air evolution under low pressure boiling conditions. Air, composed of both nitrogen and oxygen, will behave similarly. Consideration must be made for the initial concentration of each gas based on temperature.

The investigation considered two scenarios for the fan cooler heat exchanger tubes. In one scenario, the tubes can drain as the pressure in the system drops. Test Sequence 1 provides for an initially full heat exchanger tube that drains and ejects water as it boils. The second scenario considers heat exchanger tubes that are maintained full during the transient due to a vertical header attached to the tubes. Test Sequence 2 provides for a heat exchanger tube that is connected to a full vertical header, forcing steam from the tube to pass into the full header. This permits tube reflood and allows investigation of gas stripping from steam passing through the header water.

6.3.2 Test Apparatus and Conditions

The test apparatus is shown in Figure 6-2. The heat exchanger tube was a 5/8" outside-diameter copper tube and was sleeved with a 2" steam jacket to form a heat exchanger. The 10' long heat exchanger tube ran horizontally from the water supply to a 2" inside-diameter Lexan header. The header was connected to a 4" inside-diameter moisture separator by a 1.5" outside-diameter copper pipe. The header length below the entry of the tube into the header is 12". Drains from the header and moisture separator were equipped with coolers to decrease the temperature of the exiting water to approximately room temperature. Details about the test components are provided below:

Valves: All valves used in the apparatus are 3/4" bronze full port ball valves.

Vacuum Tank: The tank, which is maintained at a constant vacuum of approximately 15 in-Hg, is a Recco model #T-1421920, rated for 0 psia to 125 psig at 250°F.

Vacuum Pump: The tank vacuum is maintained at 15 in-Hg by a 50 Hz Lafert vacuum pump #3-1E-C-34-1.

Boiler: Steam is generated using either a 15-kW or 85-kW Reimers electric boiler.

Pressure Gauge: Ashcroft temperature compensated pressure/vacuum test gauges are located on the vacuum tank as well as on the 5/8" pipe between valve 1 and the Lexan header.

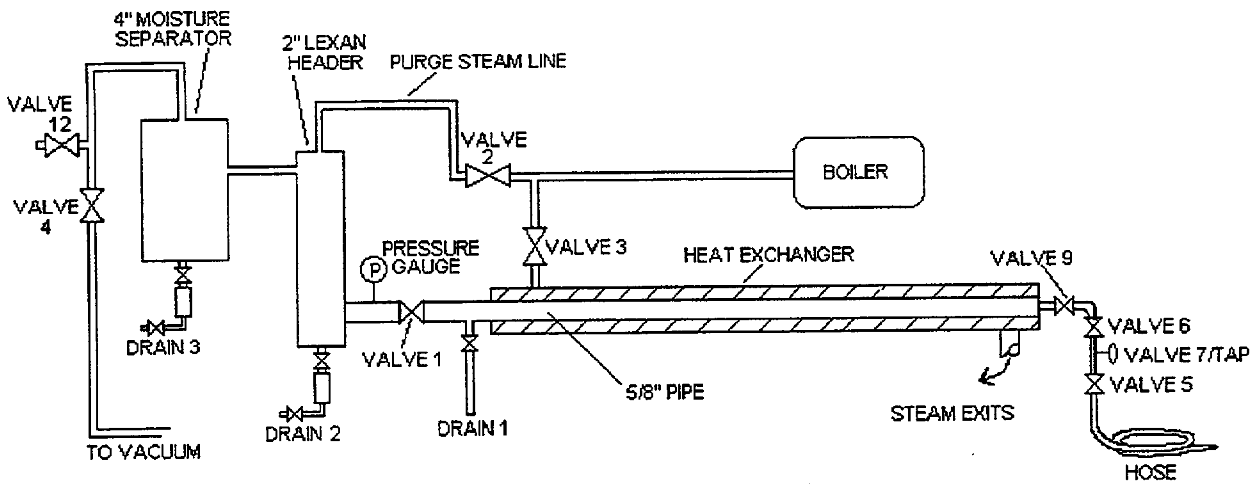


Figure 6-2
Air Release Test Configuration

Oxygen Meter: The dissolved oxygen is measured using an Extech model 407510 digital dissolved oxygen/temperature meter.

Magnetic Stirrer: A VWR magnetic stirrer and stir-bar by IKA are used to stimulate motion in the water samples. The oxygen meter requires that fluid being measured for O_2 content not be stagnant.

Test conditions were as follows:

Steam Temperature and Pressure: Two conditions were tested by using high temperature and low temperature steam. For the low temperature test, saturated steam was supplied at approximately atmospheric pressure to the jacket of the heat exchanger. For the high temperature case, saturated steam was supplied at approximately 40 psig. Temperature measurements outside of the heat exchanger indicated that the actual steam temperatures in the jacketed pipe were approximately 215°F and 255°F (±5°F) for both cases. These temperatures are prototypical for many LOCA or MSLB events.

Pressure: The pressure in the test section (inside the header and heat exchanger tube) was dropped to 15 in-Hg before steam was added to the jacket. This is prototypical of the LOOP conditions following the water flow stopping. This pressure is about mid-way between the expected transient pressure for an open loop plant (on the order of 1-2 psia) and a closed loop plant (on the order of 17 psia). The relative magnitude of the amount released from depressuization alone was discussed above. Since the removal of dissolved gas due to boiling will be shown in this testing to release far more gas (approximately 50% or 10 mg/L) than that released due to depressurization alone (approximately .03 mg/L) , the effect of pressure on the results is considered negligible.

Water: The tests are performed using "normal" tap water. The air content of this water is considered typical of that in service water systems. The air content is measured for each test.

Time: The test section was heated for 30 seconds. The time of the tests is prototypical for the LOOP/LOCA transient.

Pipe diameter: The 5/8" copper tube was within the range of the pipe sizes available in the plants. Typical fan cooler tubes range in size from 1/2" to 7/8" and are often finned. The unfinned tube used in this test lowers the outside area relative to the mass of water in the tube. Fins would transfer more heat and involve a greater percentage of the cross section in the boiling process, therefore boiling more quickly to evolve more gas. An unfinned tube will evolve less gas. Additionally, by testing two steam temperatures, the effect of increased heat transfer can be seen.

Tube orientation: The fan cooler tubes in most plants are oriented in a horizontal or near horizontal position, as was the pipe this test employed.

Header Full or Draining: The two possible conditions for an FCU header in a plant are to remain full or to drain, and these are conservatively captured in the two test conditions.

The draining test condition will allow some water to exit the tube before boiling occurs, and the water sampled after the test from drain location 2 will be a mixture of water exposed to boiling conditions and some drained prior to boiling. However, the drained amount is small relative to that expelled during boiling. A full tube would take approximately 20 seconds to drain if no heat were added. During the tests, the boiling commences in under 3 seconds so very little water escapes before boiling occurs. Additionally, it is conservative to include the non-boiled water as it will release less non-condensables and reduce the overall prediction of removed non-condensables for the whole tube.

Further, for the draining tests, the header volume below the point at which the tube enters the header, can hold the full volume of the tube. When the water is expelled from the tube, it fully enters the header below the elevation of the entry and no further mixing in the heat exchanger tube occurs.

The header full test condition is conservative relative to the actual plant since only one heat exchanger tube discharges into the header. The actual plant will have multiple tubes, each producing steam that will pass through the header water and help degas it to a greater degree than that measured in the test.

6.3.3 Test Sequence

Test Sequence 1 – Draining FCU

Initial dissolved oxygen content and temperature of the tap water were recorded. This was done by allowing water to flow from the main supply, through the 5/8" pipe, and out of drain 1 where it was collected and tested. Drain 1 and valve 1 were closed. The water supply was then shut off, leaving a water-solid heat exchanger tube.

Air was purged from the moisture separator and the Lexan header by supplying steam from the purge-steam line through valve 2 and opening the drains on the separator and header. After the purge-steam supply was cut off and the drains were closed, a vacuum of 15 in-Hg was achieved throughout the system by opening valve 4.

The steam supply to the heat exchanger was opened simultaneously with valve 1 (the discharge end of the 5/8" pipe). Steam was supplied to the heat exchanger for 30 seconds. The steam supply to the heat exchanger was then closed.

Immediately after boiling was terminated, the vacuum tank was isolated and vacuum inside the system was broken. Samples were drawn from the drain lines for air content testing.

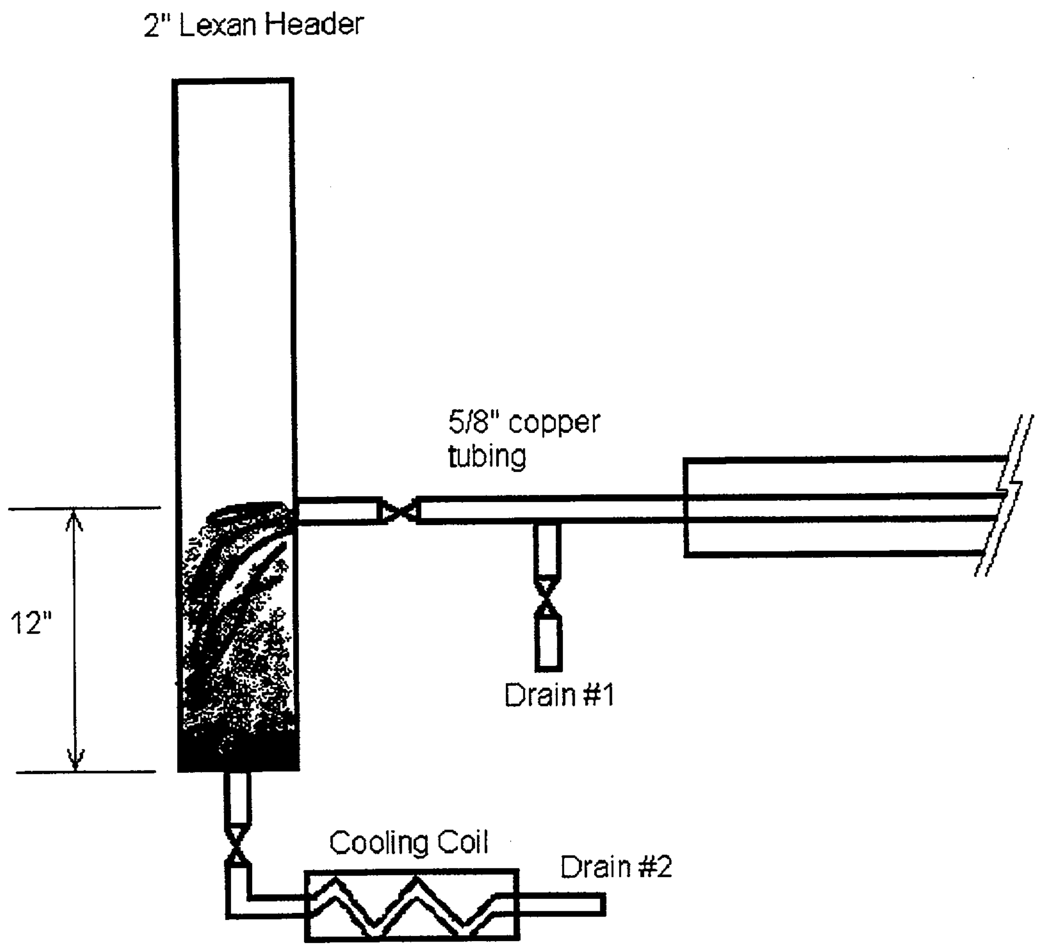


Figure 6-3
Test Sequence 1 Configuration

Test Sequence 2 – FCU with a Vertical Header

Initial dissolved oxygen content and temperature of tap water were recorded. This was done by allowing water to flow from the main supply, through the 5/8" pipe, and out of drain 1, where it was collected and tested.

Air was purged from the moisture separator and the Lexan header by supplying steam from the purge-steam line through valve 2 and opening the drains on the separator and header. After the purge-steam supply was cut off and the drains were closed, a vacuum of 15 in-Hg was applied to the system. Water was then allowed to flow through valve 1, into the Lexan header, filling it to a height of 2' above the centerline of the 5/8" pipe. The water supply was then shut off and the testing was immediately begun.

The steam supply to the heat exchanger was opened simultaneously with valve 1 (the discharge end of the 5/8" pipe). Steam was supplied to the heat exchanger for 30 seconds. The steam supply to the heat exchanger was then closed. Immediately after boiling was terminated, the vacuum tank was isolated and vacuum inside the system was broken. Samples were drawn from the drain lines for air content testing.

The dissolved oxygen content dO_2 of the header water was determined by averaging oxygen readings at three locations in the 2" Lexan header above the heat exchanger tube center-line. Steam discharging from the heat exchanger did not interact fully with the water in the lower section of the Lexan tube. Therefore, the water in the lower foot of the 2" header (below the heat exchanger tube junction) was discarded prior to collecting samples.

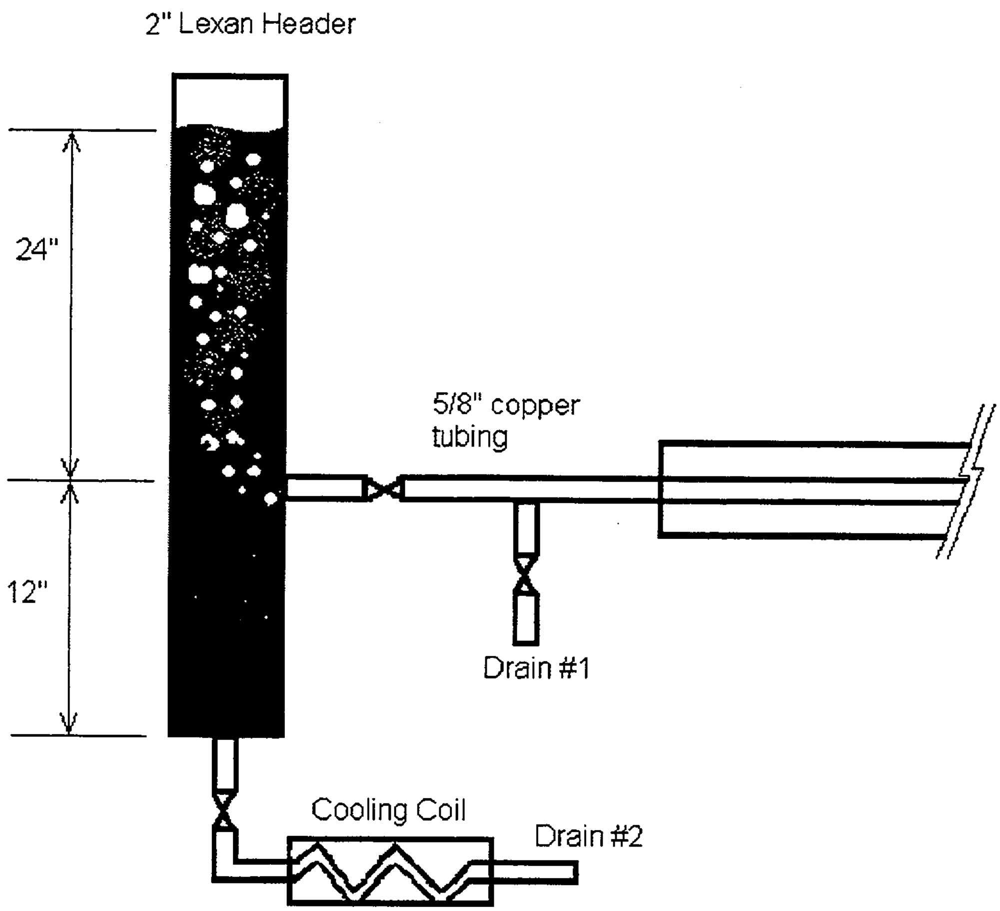


Figure 6-4
Test Sequence 2 Configuration

6.3.4 Test Results

Test sequence 1, in which the Lexan header was not filled with water, was run 25 times using steam at atmospheric pressure and 25 times using 40 psig steam. The resulting data is presented in Table 6-1, and histograms of the data are presented in Figure 6-5 and Figure 6-6. Initial oxygen readings prior to testing were approximately 10.3 mg/L. After the 30-second boiling period, the oxygen content in the water was reduced to approximately 4.6 mg/L. The mean values of released oxygen are 56.1% for the 14.7 psia steam test and 54.6% for the 40 psig steam test. The standard deviations were 4.6 and 5.9 for tests using steam at 14.7 psia and 40 psig, respectively. Taking one standard deviation below these mean values provides an oxygen release between 48.7% and 51.5%. Based on this data, an air release of 50% is recommended for use for the water that is initially in the FCU tubes.

Table 6-1
Air Release Test Sequence 1 Results

Table 6-1
Air Release Test Sequence 1 Results (Continued)

Figure 6-5
Distribution of Data Collected from Test Sequence 1 with Steam at 14.7 psia

Figure 6-6
Distribution of Data Collected from Test Sequence 1 with Steam at 40 psig

Table 6-2
Air Release Test Sequence 2 Results

Table 6-2
Air Release Test Sequence 2 Results (Continued)

Figure 6-7
Distribution of Data Collected from Test Sequence 2 with Steam at 14.7 psia

Figure 6-8
Distribution of Data Collected from Test Sequence 2 with Steam at 40 psig

[ ]

6.4 Conclusions Relative to Gas Release

The initial temperature of the water can be used to determine the initial amount of dissolved gas from the solubility curves. Figure 6-9 shows the amount of dissolved oxygen, nitrogen, or total air that is available from a source of saturated water at atmospheric pressure. The release of a percentage of this initial gas concentration represents the source of non-condensable gas in the voids that are formed during these transients.

The data from the air release testing provides evidence that water with dissolved gas will evolve significant percentages of this gas when exposed to the conditions of a LOOP/LOCA transient.

In test sequence 1, the case that represented a draining FCU, the dissolved oxygen content of the water initially in the tube was reduced by approximately [50%].

In test sequence 2, the case that represented a FCU with a header, a similar amount of gas was released for the water that was initially in the tube. The gas released from the water in the header is conservatively best represented by the water that spilled into the moisture separator and drain 3. More gas would be released in the water that remained in the header. The amount of gas released from the water in the header was approximately [24%].

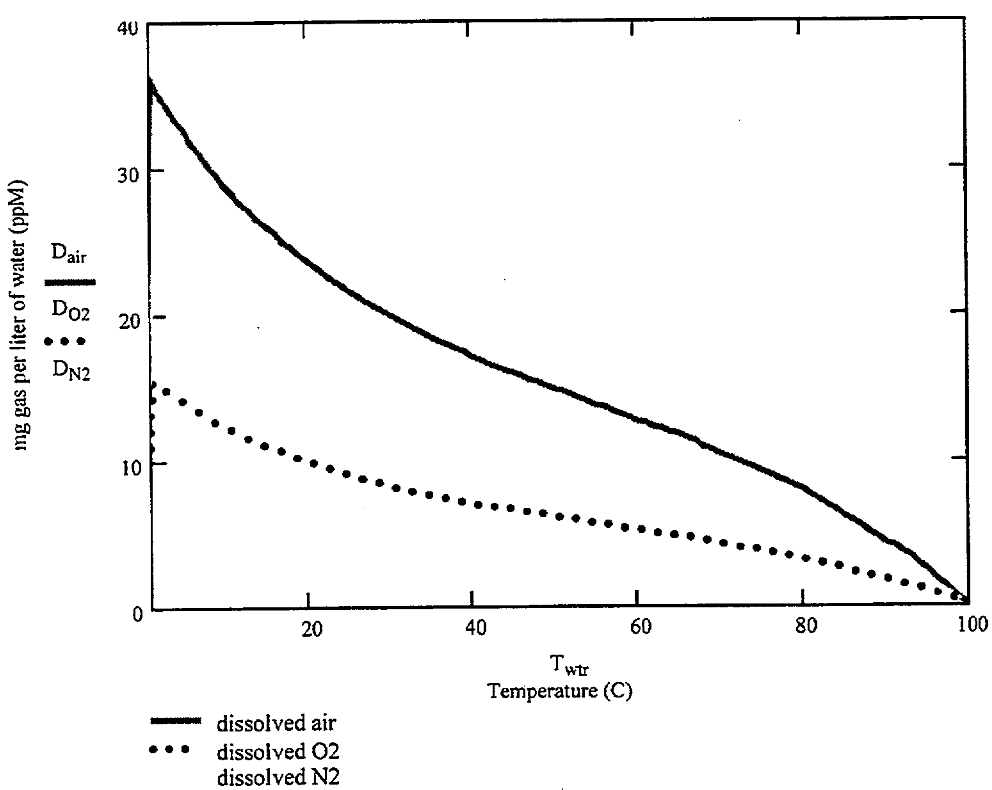


Figure 6-9
Solubility of Air, Oxygen, and Nitrogen in Water at Atmospheric Pressure

7
CONDENSATION INDUCED WATERHAMMER

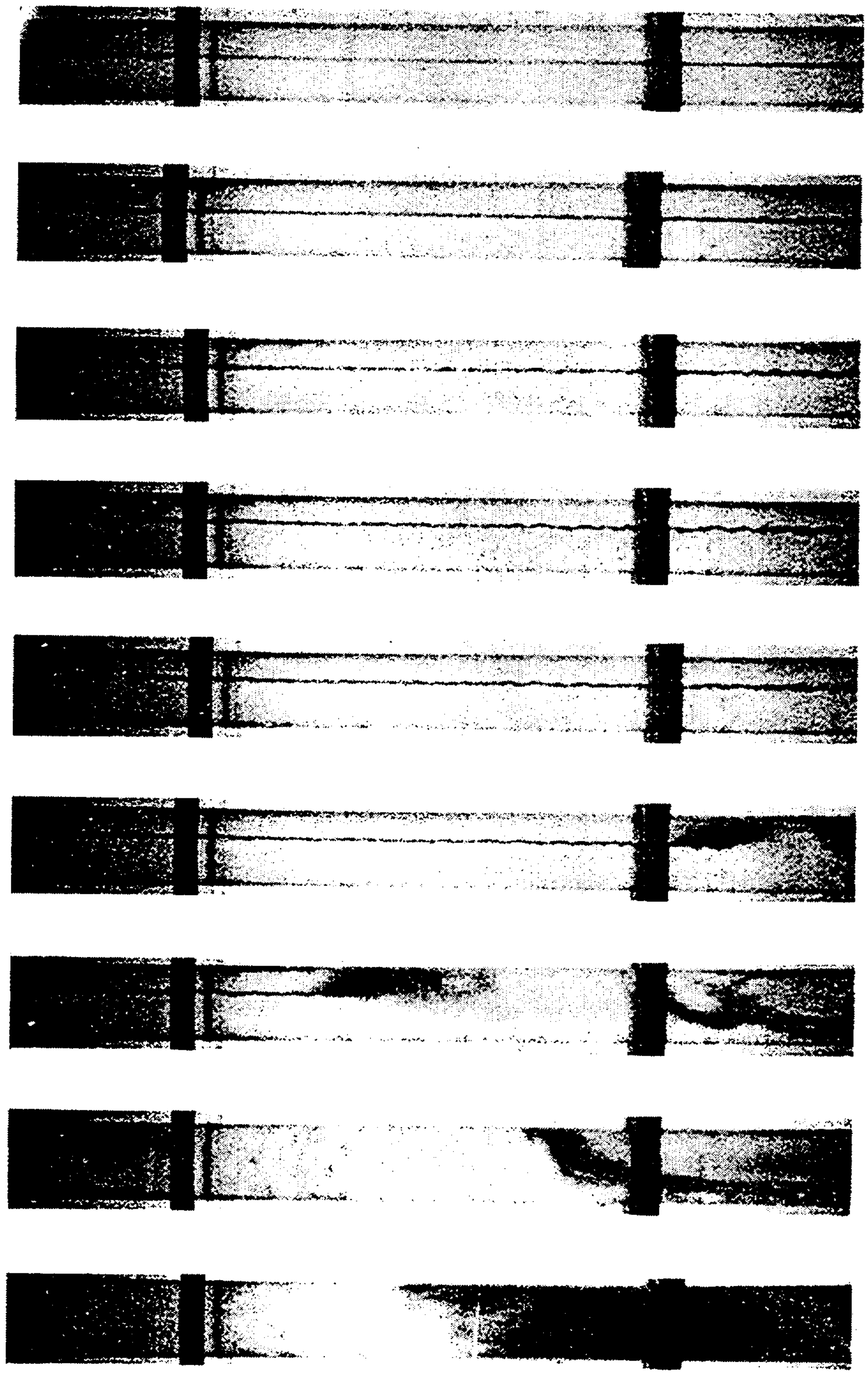
Condensation induced waterhammer (CIWH) occurs when steam bubbles become trapped, rapidly condense, and the surrounding water is driven to rapidly close the void. Much testing has been performed prior to this program that provides a clear understanding of the CIWH mechanism. It was with a basic understanding of the mechanism of CIWH and the parameters of interest that a conservative series of tests were developed in order to better understand the behavior in the FCU system. With the results of the testing, justification for a system screening method was developed. The next section describes the occurrence of CIWH and the parameters of importance. The following sections describe an analytical method for comparison to the testing, the testing that was performed as a part of this project, the applicability of the test data to other pipe sizes, and the recommendations for system qualification.

7.1 CIWH Occurrence

Figure 7-1 and Figure 7-2 show a series of frames selected from a high-speed motion picture of several CIWH occurrences [13]. The pictures were taken in horizontal pipes, 1.5 inches in inside diameter and up to 2 meters long. Tap water at room temperature entered from the left and was discharged into a plenum at the right. The plenum was supplied with steam generated from a large boiler that was supplied to the testing laboratory. The steam was slightly above atmospheric pressure. Some of the steam was condensed on the cold water as it passed through the test section. Figure 7-1a to e show a gradually increasing interface roughness as the water flow rate was increased and the flow area available for the condensing steam decreased.

Figure 7-1f shows a transition to slug flow. It occurred in only 0.02 seconds. The condensation of the steam trapped to the left of the slug causes the pressure in the bubble to drop and the liquid slug to accelerate to the left. The slug grows and continues to move to the right, until, in Figure 7-1j, the pipe has filled with a bubbly mixture. In Figure 7-1k, the mixture has clarified and a new tongue of liquid has started to advance to the right while vapor begins to advance to the left. The surface of the liquid becomes smooth. The same process repeats itself within about 2 seconds when a new waterhammer occurs. This is typical for CIWH.

These pictures were taken with back lighting so an emulsion of small drops in the gas phase (or small bubbles in the liquid) scatter the light and make the mixture look black. Both pure liquid and pure vapor in these pictures appear white. Turbulence and entrainment of bubbles at the interface is evident.



a. t = 0 s

b. t = 7.99 s

c. t = 14.42 s

d. t = 15.96 s

e. t = 17.96 s

f. t = 17.98 s

g. t = 18.01 s

h. t = 18.04 s

i. t = 18.09 s

Figure 7-1
Water Slug Formation and Periodic Waterhammer

j. t = 18.16 s

k. t = 18.43 s

l. t = 18.51 s

m. t = 19.41 s

n. t = 20.41 s

o. t = 20.53 s

p. t = 20.66 s

q. t = 20.68 s

r. t = 20.70 s

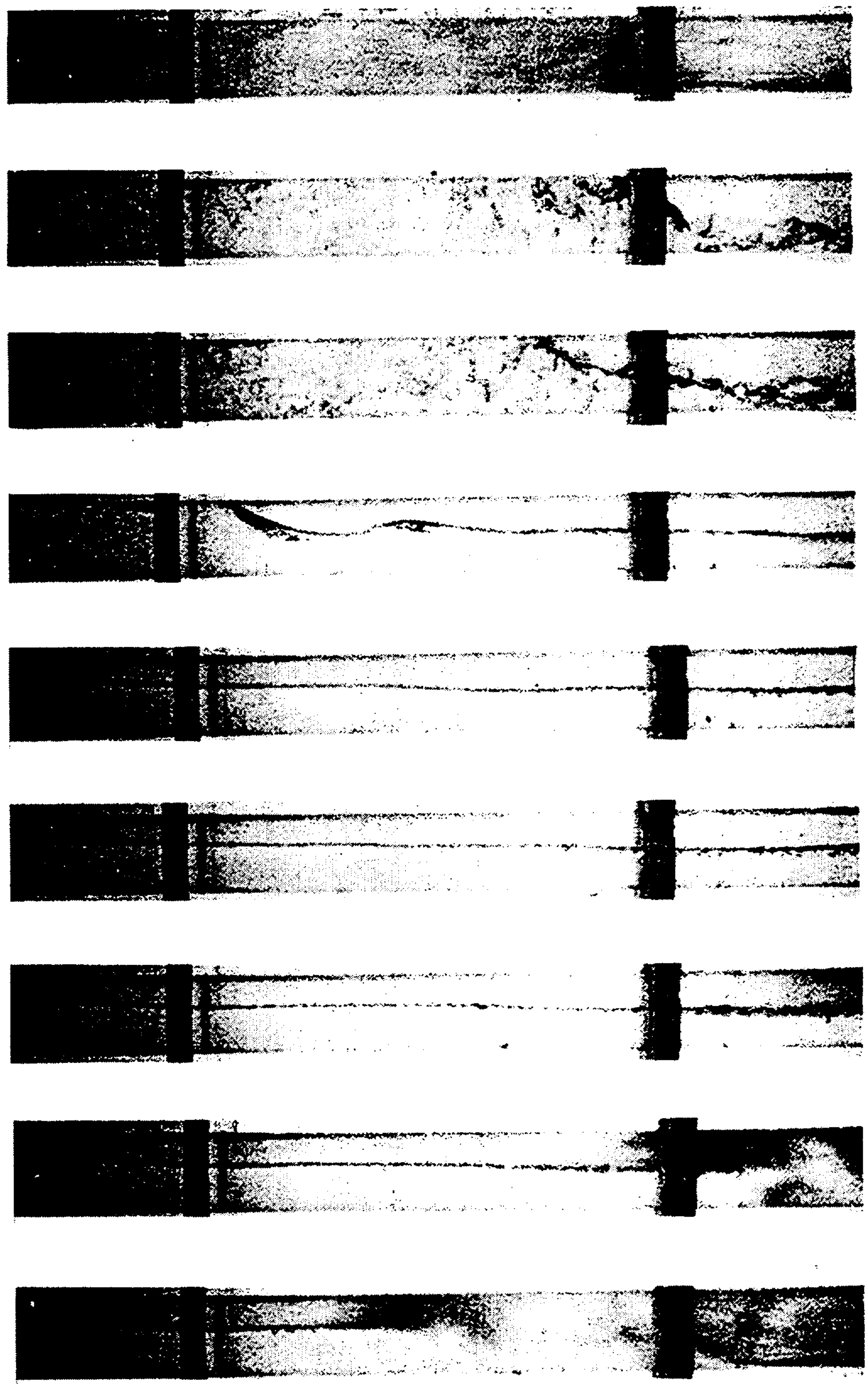
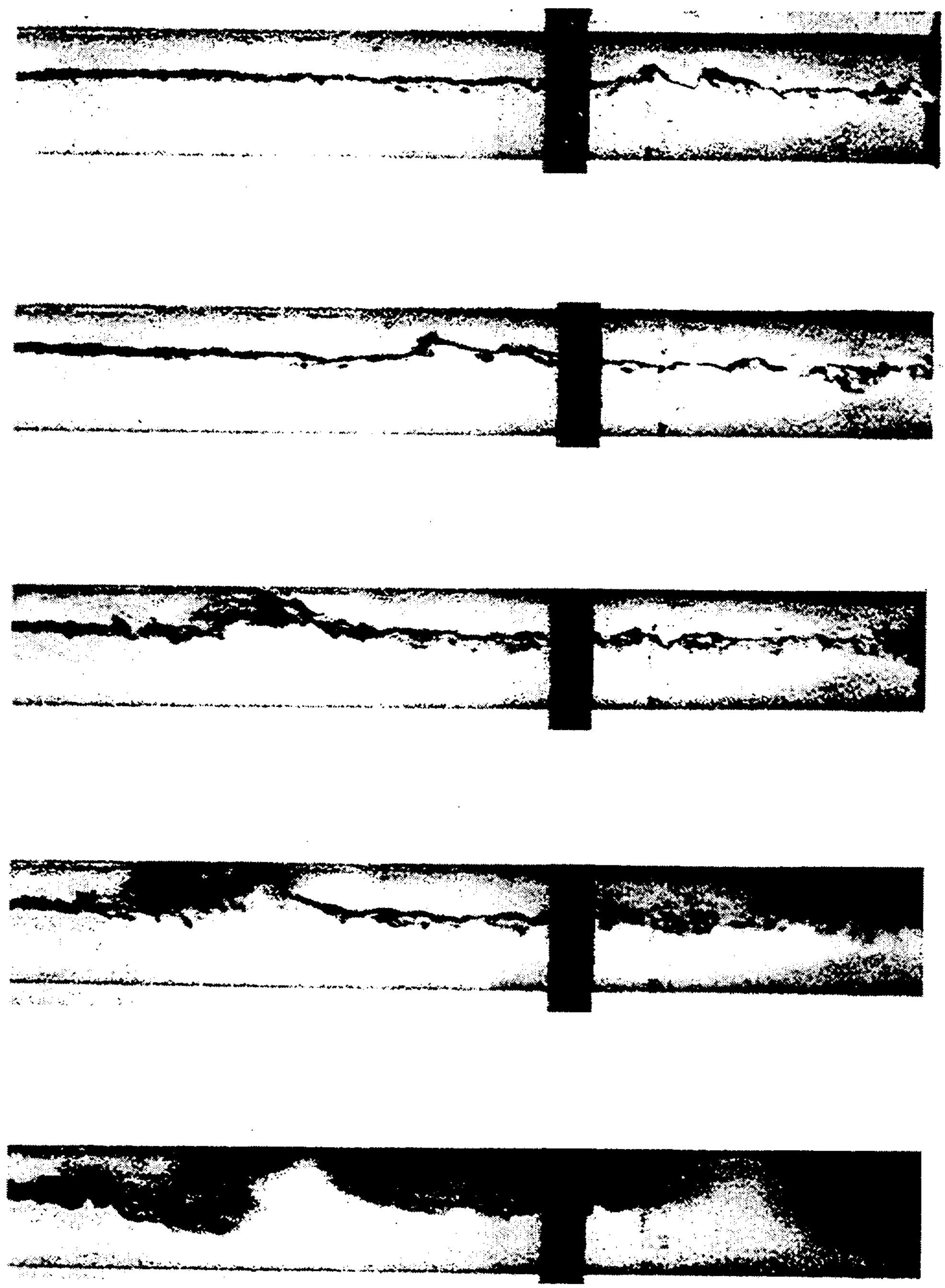


Figure 7-1
Water Slug Formation and Periodic Waterhammer (Continued)

Figure 7-2 is an enlarged picture of a waterhammer in which two slugs started to form. It is evident that not every CIWH event looks the same, or produces the same pressure signature. The details of the steam/water interface change from event to event. This natural variability accounts in part for the variability seen in peak pressure and pressure pulse duration.

In addition to understanding the sequence of events leading to CIWH, these pictures make clear that an intimate mixture of the phases is typical and that non-condensable gas is present.



a.
t = 0 s

b.
t = 0.16 s

c.
t = 0.28 s

d.
t = 0.30 s

e.
t = 0.31 s

Figure 7-2
Details of Water Slug Formation

7.1.1 Flow Regime

A pipe with stratified, subcooled water and a source of steam creates the potential for transition to slug flow. This is a key element for the initiation of a condensation induced event. Investigations by Griffith and Bjorge [13] demonstrate the relative steam and water velocities required to initiate this event. These velocities can be achieved by rapid steam condensation on exposed subcooled water. Velocities are higher at small void fractions, since the cross sectional flow area for the steam is small. Steam velocity decreases as void fraction increases, and transition to slug flow is not likely at void fractions greater than 0.5 [14].

During the LOOP/LOCA transient, a horizontal pipe can become partially filled during the void formation phase and during refill. During the void formation phase, the velocity of the draining fluid is likely to produce stratified flow that can transition to slug flow and cause waterhammer. Investigations by Min [15] and Silva [16] show that at high drainage velocities, the frequency of waterhammer recurrence in a single horizontal line is diminished, but at least one waterhammer was likely to occur. Testing performed as part of this TBR preparation effort confirmed that high drainage rates did not mitigate waterhammer occurrence.

For refilling pipe, CIWH could occur if the water in the horizontal pipe becomes stratified and can transition to slug flow. Studies conducted by Wallis et al. [17] established a minimum flow rate necessary to prevent transition to slug flow. This correlated to a Froude number of 0.5. A reasonable level of conservatism suggests that if the pipe is filled at a rate greater than velocity determined using a Froude number of 1.0, then the risk of CIWH is negligible for all pipe sizes. This velocity is defined based on a Froude number calculated as follows:

$$Fr = \frac{V}{\sqrt{g \cdot D}} \qquad \text{7-1}$$

7.1.2 Condensation Rate

Vigorous condensation is another parameter required for CIWH to occur. The very rapid decrease of pressure in the steam void (void collapse) is a direct result of the condensation rate. For this rapid condensation to occur, the draining fluid must have sufficient subcooling relative to the steam and there must be sufficient surface exposed on which the steam can condense.

The subcooling of the fluid is the temperature below the saturation point for a given pressure. A transition temperature of 36°F subcooling of the fluid has been used by Griffith [18]. If the draining fluid is not subcooled more than 36°F, the condensation rate is insufficient to produce significant waterhammers.

The exposed surface area contributes to the overall condensation rate of the available steam. In a vertical pipe, condensation occurs on the water surface (equal to the cross sectional area of the pipe) and piping as it becomes exposed. The pipe and surface of the fluid will quickly become heated and condensation rates will slow. However, when the steam/water interface crosses into a horizontal pipe, a tongue of steam will progress along the top of the pipe, greatly increasing surface area, and bypassing the heated surface of the draining fluid. Condensation rates increase exponentially, and the transition to slug flow and CIWH can occur. These processes are shown in Figure 7-3.

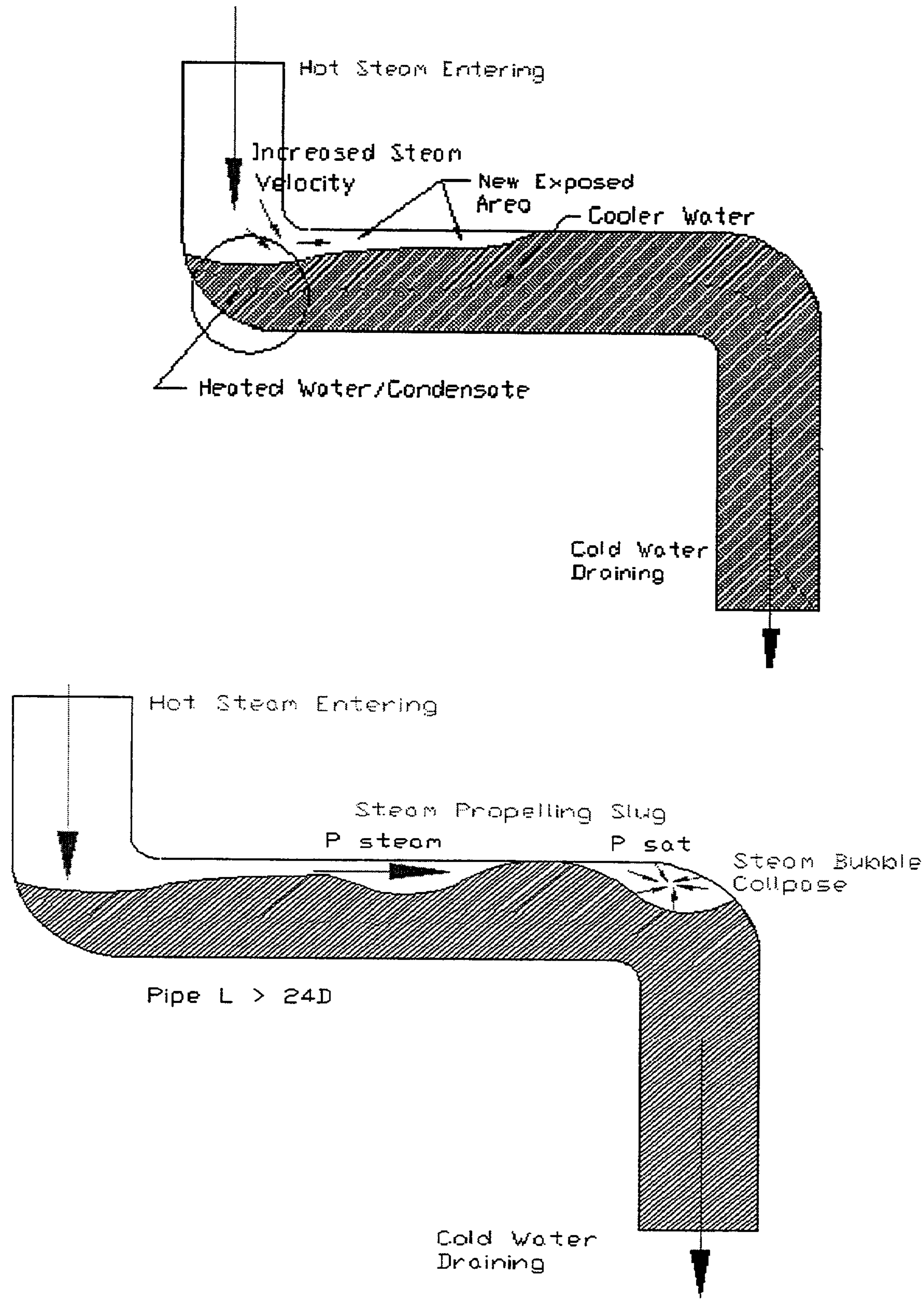


Figure 7-3
CIWH Process

7.1.3 Pipe and Slug Geometry

Condensation induced waterhammers occur in long horizontal or near horizontal piping in which a stratified flow regime exists at the onset of transition to slug flow. A screening criteria for "horizontal" piping has been proposed by Griffith [18], it states that the pipe should be declined no more than 2.4° (0.5 in/ft) to the horizontal for waterhammer to occur. Larger declination angles produce too little cross surface flow and therefore lower shear stresses, limiting the ability to transition to slug flow. It should be noted that other types of waterhammer can occur in steeply inclined or vertical pipes (water-cannon, for example), but these are not caused by stratified, draining flow. Sloped pipe or other special geometry cases should be addressed on an individual plant basis.

Another geometric criterion for CIWH to occur is a sufficient length of horizontal run. In the Reference [13] tests, it was observed that no waterhammer occurred in piping with a length less than 24 diameters. In pipe with a length greater than 48 diameters, waterhammer always occurred. These tests were performed near atmospheric conditions. Therefore, for the service water systems considered here, a minimum length to diameter ratio (L/D) of a horizontal pipe must be at least 24 in order to allow the occurrence of CIWH [18].

7.1.4 Bubble Collapse

Once a steam bubble is trapped, rapid condensation causes the surrounding water to rush in and close the void. The water is driven into the void by the pressure difference between the system pressure and the low pressure in the void. The pressure in the void will be the saturation pressure corresponding to the temperature of the surrounding water. The magnitude of the waterhammer is proportional to the velocity of the water driven into the closure. The closure velocity is related to system pressure at the time of the void collapse. In the FCU system, the system pressure around the void will be low (typically sub-atmospheric) and the resulting velocity will be limited. Low-pressure systems generally do not possess sufficient energy to create large CIWH. A minimum range of system pressure has been proposed in NUREG/CR-6519 [18] to be approximately 100 to 300 psig for damaging waterhammers to occur.

7.2 Analytical Model

Waterhammers of interest to the events described in GL96-06 consist of pressure waves formed from a rapid change in fluid momentum. The CIWH and CCWH initiate during different times of the transient and arise due to different phenomena, but they share the characteristics of creating a pressure wave or pulse of finite duration. This pulse travels away from the initiation point and can cause unbalanced forces in the piping system.

Waterhammer magnitude can be calculated using the Joukowski equation (Equation 7-2 [6]), which relates pressure pulse magnitude to the momentum change in the water. The pressure pulse magnitude ΔP is a function of the water density ρ, the sonic velocity C, and the change in velocity of the water slug ΔV.

$$\Delta P = k \cdot \rho \cdot C \cdot \Delta V \qquad 7\text{-}2$$

The Joukowski equation applies at a single location in a pipeline, and is valid in a frictionless system until a reflection is received from another location in the system. Friction generally has only a minor influence, unless very long pipe lengths are being considered, which is not the case here. The Joukowski equation is useful for providing conservative, bounding solutions if the appropriate terms are used. A discussion of each term in the Joukowski equation is presented below.

7.2.1 Constant (k)

A constant term, k, is used to model the surface on which the void closure impact occurs. For a closure against a hard surface such as a valve or closed pipe end, $k = 1.0$. For a closure against another water column, $k = 0.5$. For all condensation induced waterhammers occurring during voiding of the FCU system, $k = 0.5$ is appropriate.

7.2.2 Density (ρ)

The density term is the density of the fluid that is closing the void. In most waterhammer analyses, it is appropriate to use the density of the water, exclusive of the void.

7.2.3 Sonic Velocity (C)

The sonic velocity is the speed at which a pressure wave travels through the fluid medium. This term is important for determining both the magnitude of the pressure pulse and the time that the wave travels through the piping system. This transit time is important to the dynamic loading of the structure.

7.2.4 Velocity Change (ΔV)

The velocity change that produces a waterhammer pressure pulse is the reduction in velocity of the advancing water as it impacts the stationary water on the other side of the void. The entire velocity of the advancing water can be assumed to be reduced to zero at impact ($\Delta V = V$), although if the impacted surface has a velocity, the relative velocity between the oncoming and impacted surfaces will determine the magnitude of the waterhammer.

A water slug is accelerated into the steam void by the differential pressure acting across the water slug ($P_v - P_o$) as shown in Figure 7-4. The velocity that is achieved by the slug is usually limited by inertia and can be determined from the energy balance [19]:

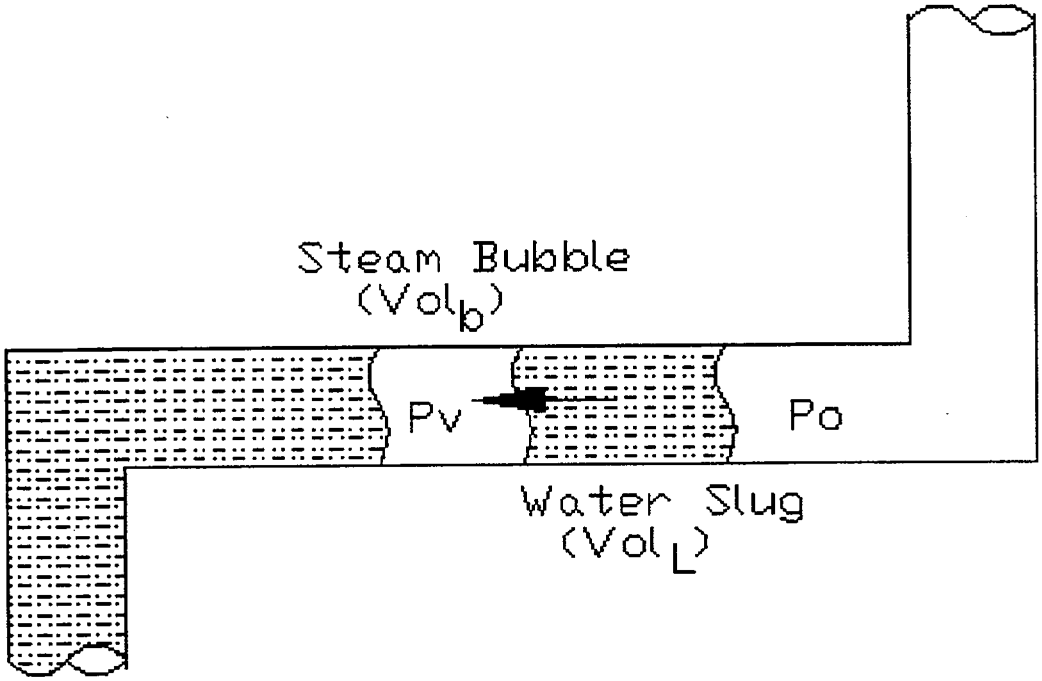


Figure 7-4
Condensation Induced Void Closure Model

$$\frac{1}{2}\rho\cdot(Vol_L)\cdot V^2=(P_o-P_v)\cdot Vol_b \qquad 7\text{-}3$$

Where:

Vol_L, Vol_b	=	volumes of the water slug and steam bubble, respectively
ρ	=	density of liquid
V	=	velocity
P_o	=	system driving pressure
P_v	=	pressure in void

As an approximation, the relative steam and water volumes can be related to the average void fraction α by:

$$\frac{Vol_b}{Vol_L}=\frac{\alpha}{1-\alpha} \qquad 7\text{-}4$$

The velocity term is therefore:

$$\Delta V = V = \sqrt{\frac{2\cdot(P_o - P_v)}{\rho}\cdot\frac{\alpha}{1-\alpha}} \qquad \text{7-5}$$

7.2.5 Pressure Pulse

If the velocity term (Equation 7-5) is substituted directly into the Joukowski equation (Equation 7-2), the following equation is produced:

$$\Delta P = C\sqrt{2\cdot(P_o - P_v)\cdot\rho\cdot\frac{\alpha}{1-\alpha}} \qquad \text{7-6}$$

The equation for ΔP is independent of pipe diameter.

This waterhammer pressure pulse is predicted to occur and load the system for a defined amount of time. In a classical prediction model, the pressure pulse moves from the point of origination, through the fluid to the free surface, and reflects. Based on this model, the duration of the pressure pulse t_d is the distance to travel out and back ($2L_w$), divided by the speed at which it travels (the sonic velocity, C).

$$t_d = \frac{2L_w}{C} \qquad \text{7-7}$$

7.2.6 Impulse

One factor limiting the structural significance of the condensation induced waterhammer is the magnitude/duration relationship of the waterhammer pulse. For a water slug which is accelerated into a steam void by the system pressure, the pulse magnitude is proportional to the sonic velocity as shown in Equation 7-6 while the duration is inversely proportional to the transit time of the pulse through the water slug as shown in Equation 7-6. If the sonic velocity is low due to released non-condensables, the duration can be long, but the pressure pulse magnitude will be small. If there are few released non-condensables, the pressure pulse can have a high magnitude, and, for the same reason, the duration will be short. This inverse relationship demonstrates the limited amount of energy available to load a piping structure.

7.3 Testing

Testing of condensation induced waterhammer events was performed to characterize the magnitudes of pressure pulses generated during the voiding of piping configurations that were similar to those found in nuclear power plants. The pressure magnitudes were compared to the magnitudes predicted by the analytical model presented above.

Test parameters were selected that would be conservative relative to the expected conditions in the power plant. The next section defines the important parameters that were selected for the test.

7.3.1 Test Conditions

Conditions that were bounding of those that would be found in plant service water systems were used to produce waterhammers in the testing. The test parameters were all chosen so that the test results would be conservative. The following is a description of key test parameters with a comparison to the in-plant conditions.

- **Geometry:** The horizontal test section was 4 inches in diameter and approximately 22 feet in length, providing a length of 66 diameters. This met the minimum 24 diameters required for CIWH, and the results show that multiple waterhammers occurred in the test section as it was draining. The 4" pipe diameter was above the point at which surface tension effects would be significant, while being on the lower end of typical pipe diameters for a SW system. This is representative or conservative compared to an actual plant system.
- **Steam Pressure:** The supplied steam pressure at the initiation of the test was 10 to 15 psig. This supply pressure is larger than the pressure in SW systems that lose pump power and drain. System pressures in open loop plants generally remain below atmospheric throughout most of the transient. In closed loop systems, boiling is not expected at local pressures above approximately 15 psig. The larger pressure makes the test conditions conservative relative to the plant conditions.
- **Steam Quantity:** The amount of steam available for the test section was far greater than the amount condensed during the test. This was verified by the occurrence of only a modest system pressure reduction of approximately 3 to 5 psig during the test and a rapid pressure recovery at the specific time of the void collapse. The available steam was able to "keep up" with the rapid condensation on the water and pipe surfaces when the horizontal pipe was uncovered in the test. In actual systems, the piping between the FCUs and the CIWH location would be much longer than the test, and the ability of the system to supply the large quantity of steam that is condensed may be limited by choking at restricting locations and losses in the piping. Since the large quantity of available steam in the test maintains the pressure at a higher level than is likely in most plant systems, this test condition is conservative.
- **Steam Air Content:** The supplied steam used in the test was created from water that was deaerated by being boiled and cooled prior to being supplied to the test steam generator. Non-condensable bubbles in the trapped steam void or adjacent water would reduce the magnitude of the waterhammer impact. Waterhammer peak pressure is reduced due to air causing lower sonic velocity in the water, cushioned void collapse, and slower steam condensation rates. In the power plant, air will travel with the steam and accumulate at the

condensing surface as the steam is consumed. Since the steam in the test was deaerated, concentrated air near the trapped steam bubble was greatly reduced. This produced conservative test conditions. For a plant with a closed system there is usually a gas cover such as nitrogen in the makeup or surge tank, which would also lead to non-condensable gas bubbles. The water in open or closed service water systems will have moderate to high levels of dissolved non-condensables that will be released when the water boils.

- **Water Air Content:** The tests were performed using two different water conditions for the draining water. "Normal" water, tap water with no control on dissolved air content, was used in one test set. In the second, deaerated water (pre-boiled to reduce dissolved air content) was used. Dissolved non-condensables in the water will tend to come out of solution and reduce waterhammer magnitudes. The water in the service water systems is not expected to be deaerated. The "normal" water tests are considered to be prototypical of the power plant and the deaerated tests are considered to be conservative.
- **Thermal Layer:** The condensation rate on the exposed water in the horizontal pipe will greatly influence the waterhammer magnitude, as the condensation rate controls the shift of flow regime into a slug flow regime that allows steam to become trapped. Lower condensation rates yield lower steam velocities along the surface of the water and reduce the likelihood of slug flow regimes. Hot water in the vertical column draining into the pipe will reduce the condensation rate and reduce the likelihood of waterhammer. The draining water will develop a thermal layer or section of higher temperature liquid between the hot steam and the cold draining water due to condensation of steam on the newly exposed cold pipe and the pre-heating of the water as the void forms. The test conditions used only cold water in the vertical draining pipe, with no thermal layer. The presence of only cold water in the test maximizes the likelihood of waterhammer occurring, produces unrealistically high condensation rates and larger waterhammers than would be expected in the plants.

The tests performed over-predict the magnitude of the waterhammer because of the higher than expected system pressure, no gas in the steam, and no thermal layer. The waterhammers measured in the tests would be larger than those expected in the plants.

7.3.2 Piping Configuration

The piping system consisted of a long horizontal section in which condensation induced waterhammer, similar to those that would occur during the void formation phase of the LOOP/LOCA or LOOP/MSLB transient, could be created. The length to diameter ratio of the test section was greater than the 24 "rule of thumb" [18] for piping length required to get CIWH.

Subcooled water was used in the test section. A simplified cross section of the test section is presented in Figure 7-5 and an isometric is presented in Figure 7-6.

The voiding process was initiated by supplying steam at a pressure up to 15 psig in the vertical riser pipe. The steam supply needed to provide sufficient steam to the piping section so that the "system" pressure of the steam did not drop due to rapid condensation on the water surface and pipe walls when the horizontal pipe was uncovered. The steam supply was capable of supplying sufficient steam to keep up with the large amount of steam that was condensed as the voiding proceeded into the horizontal pipe section. There was no appreciable supply pressure drop as the condensation process occurred.

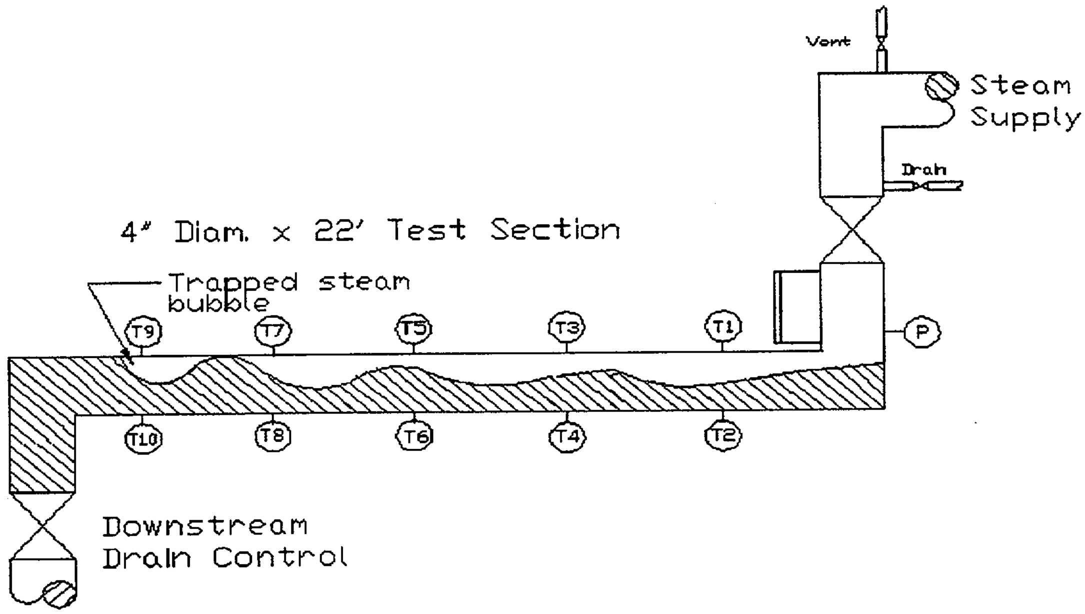


Figure 7-5
Test Section Schematic

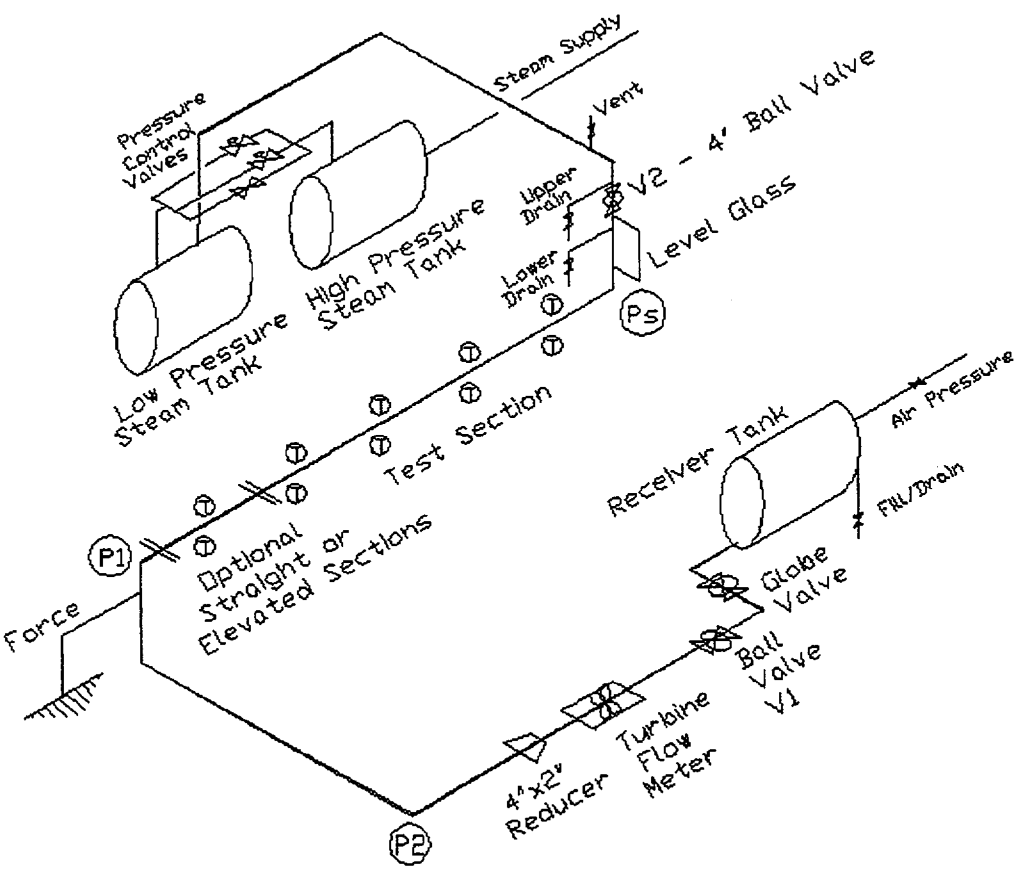


Figure 7-6
Isometric of CIWH Test

The instruments and other devices are designated as follows:

P – pressure transducers measuring steam pressure (Ps), traveling pressure pulse (P1, P2)

T – thermocouples (T1 - T9 odd numbers on top, T2 - T10 even numbers on bottom)

Force – Axial load was measured at a pipe restraint instrumented with strain gages

The steam supply and test section were constructed of 4" schedule 40 butt-welded pipe. The test section was leveled to horizontal.

Downstream of the test section, drain piping removed water from the test section to a receiver tank. This pipe had a 4" nominal diameter at the test section and reduced to a 2" diameter approximately 10 feet downstream of the test section.

The steam supply piping to the test section had a 0.5" diameter vent at the highest point above the vertical pipe leading to the test section. A drain line was mounted directly above (within 2") of the vertical 4" ball valve (V2). A vent line was also installed directly below (within 2") of the ball valve.

7.3.3 Components

7.3.3.1 Valves

Several valves were used to control the fluid conditions in the test section, including two ball valves used to isolate the test section, one globe valve used to modulate drain rate, and two steam pressure control valves used to supply steam pressure to the test section.

One 4" Apollo carbon steel, full port ball valve was used at the upstream end of the test section. This valve isolated the steam supply to the test. One 2" Apollo carbon steel, full port ball valve in the downstream drain portion isolated the test piping from the receiver tank. These valves were operated automatically using piston type air operators. An internal rack and pinion provided the 90° turn motion required to close the valves. These operators featured springs to allow the valve to fail in a predetermined position.

A 2" Y-pattern globe valve was used to control the flow rate from the test piping to the receiver tank. The Y-pattern globe valve was selected based on its lower pressure drop characteristics. The globe valve required 12 turns to move from fully closed to fully opened positions. Valve position was designated based on the number of turns open.

Two TLV COSR-16, internal sensing steam pressure control valves were used to supply the steam to the test at a desired pressure. Two valves were used in order to assure both fine control, through the 2" valve, and large capacity, through the 2½" valve. This was accomplished by setting the larger valve supply pressure to approximately 1/2 psi higher than the small valve. The valves were rated to supply a flow rate of up to a total of 8,000 lbm/hr at the desired pressure. A bypass line around the control valves was used for initial heating of the system. This bypass line was operated by opening a ball valve.

7.3.3.2 Tanks

The CIWH test configuration had four tanks, three of which are shown in the isometric. All tanks were ASME stamped vessels, rated to 125 psig. The Low Pressure and Receiver Tanks were rated also for vacuum service. Pressure relief valves set to 100 psig were installed on each tank.

High Pressure Steam Tank: The high pressure steam tank stored the required steam for the test. This tank contained 200 gallons of steam at a pressure of approximately 80 psig. The high pressure steam tank could provide up to 5 pounds of steam for the test. This large volume and high pressure assured an adequate volume of steam for each test.

Low Pressure Steam Tank: An 80-gallon tank was used to supply the test section. This expanded volume downstream of the control valves allowed the system to keep up with the changing demand for steam and modulated the pressure fluctuations in the test section. As a secondary function, it allowed the steam to dry by shedding water droplets as it slowed in the tank.

Receiver (Vacuum) Tank: A vacuum tank served as the receiver for the draining water from the test section. A vacuum was used to draw the flow to achieve the flow rate desired while maintaining a low pressure in the system.

Water Treatment Tank: An 80-gallon tank was used for water treatment in the CIWH tests. This tank was equipped with an induction heating coil inserted into a 3" NPT port at approximately 1/3 of the tank height. This heater was used to boil the water in the tank before it was fed to the boiler. The pre-boiling process was used to deaerate the water used to create steam for the tests, and the water solid path ensured that no air would be picked up between the treatment and the boiler.

Measurements of the dissolved oxygen levels of the supply water were made to assure that steam with as little non-condensable gases as possible was created in the boiler. The water supplied to the boiler averaged 3 ppM dissolved oxygen. This is below the aeration level for open raw water systems which is typically 6-8 ppM.

7.3.3.3 Steam and Air Supply Systems

Steam was generated using a Reimers electric boiler capable of supplying steam at 85 psig to the HP tank. Steam was piped directly to the HP tank and was isolated during the tests using a ball valve.

Laboratory air pressure at approximately 80 psig was used to pump water and position the two power operated ball valves. Air to position the ball valves was controlled using 5-way solenoid valves. Air was also used to pressurize the water receiver tank to pump water through the test section and into the vertical piping above the 4" ball valve.

7.3.3.4 Pipe Support System

The 4" steam supply and test section piping was supported for deadweight approximately every 15 feet. Rod hangers supported the elevated piping from the tanks to the test section. The test section was supported with simple deadweight supports bolted to the floor and equipped with low friction, teflon/stainless steel slider plates to minimize friction. The test section was also restrained with U-bolts to hold the piping down on the deadweight supports.

One axial support at the end of the test section was designed to provide restraint for the unbalanced loads in the horizontal test section. This restraint was instrumented with strain gages along the strut section so that the load could be determined. The engineered restraint was made from standard Bergen-Patterson parts including a lug welded to the elbow at the downstream end of the test section, a pinned connection to a 1" threaded rod, and a pinned lug welded to the support steel. The vertical support steel was constructed of 4" × 4" tube steel approximately 48" high and welded to a 12" × 12" × 1" base plate. The base plate was anchored to the floor using 3/4" Hilti concrete anchors.

7.3.3.5 Instrumentation

Flow meter

A 2" turbine type flow meter (Hoffer Flow Controls model HO2X2-15-225-B-1MX-F6CS) was used to measure the draining water flow rate. This instrument provided flow measurement over a range of 15 to 225 gpm.

Steam Flow Rate

An orifice was used to measure steam demand to the test. The orifice was placed in the 4" piping from the Low Pressure Tank. The orifice bore was 2.3805 inches and was fitted with corner taps.

Pressure Transducers

Sensotec pressure transducers were used to measure steam supply pressure, waterhammer pressure pulse, and the differential pressure across the flow orifice. Pressure transducers used in the steam supply section of the test apparatus are Sensotec Model Super TJE ultra precision absolute transducers with a range of 0 to 50 psia. Sensotec's Super TJE model has an accuracy of ±0.05% full scale, and temperature effect on span and zero of 0.0015%/°F. Pressure transducers used to measure the waterhammer pressure pulse were either 0-1000 psig or 0-3000 psig Sensotec Model TJE transducers. Sensotec Model TJE pressure transducers have an accuracy of ±0.1%, temperature effect on span and zero of 0.0025%/°F, and frequency responses of 0.088 ms (≈ 11 kHz) and 0.037 ms (≈ 27 kHz) for the 1000 psig and 3000 psig transducers respectively. Data was acquired from the transducers at a rate of 4000 Hz.

Static Pressure Measurements

Each of the tanks was fitted with a 6" Ashcroft dial pressure indicator. These instruments were used to set pressures prior to test initiation. The ranges of each indicator is as follows:

- HP Tank 0 - 100 psig
- LP Tank 30 in-Hg - 30 psig
- Receiver Tank 30 in-Hg - 30 psig

Thermocouples

Thermocouples penetrated the pipe wall at ten locations along the top and bottom of the horizontal test section. Each thermocouple penetrated approximately 0.25" to 0.5" into the flow. The thermocouples permitted the measurement of the progress of the steam and shape of the steam/water interface in the test section as the horizontal pipe drained. The thermocouples were sampled at 1000 Hz, although the response rate of these instruments was approximately 0.1 sec.

The thermocouples are designated T1 - T9 (odd numbers) on the top of the pipe and T2 - T10 (even numbers) on the bottom of the pipe.

Force Measurement

The pipe restraint was instrumented with strain gages and calibrated with a load cell to permit the measurement of axial load on the test section produced by the generated waterhammer. The force on the restraint was measured at 1000 Hz.

Level Indicators

The level of the fluid was visually monitored with sight glasses in two locations for the CIWH tests. These locations included above and below the 4" ball valve and in the receiver tank.

7.3.3.6 Test Control Program

A program was written utilizing the LABView software package to automate valve operation and data acquisition. The test control program output drove relays that provided 120V power to position the solenoid valves.

The control program was operated in two modes. The first mode featured real time control, during which valves could be positioned and instruments could be read and adjusted. This operating mode was used during the filling of the system and preparation for testing. The second mode of operation was a programmed sequence of steps in which the valves were automatically operated and data was collected and written to a file. This automated mode of operation was used during the test to ensure consistent operating conditions.

7.3.3.7 Oxygen Meter

The amount of dissolved oxygen dO_2 in the test water was measured using an Extech model 407510 digital dissolved oxygen/temperature meter. The meter measured dissolved oxygen in water from 0 to 19.9 parts per million (ppM) and in air from 0 to 100%. Parts per million (ppM) is equivalent to mg/L.

The dissolved oxygen level was used as a basis for determining total dissolved air in the fluid. It was assumed that the dissolved oxygen remained proportional to the dissolved air in the system. This appeared true except when water was allowed to remain stagnant in the system, and some oxygen was scavenged by corrosion. Therefore, the system was refilled between tests with fresh water as described in the test sequence.

7.3.3.8 Data Acquisition Equipment

Data was sampled from the various instruments through two multichannel boards. A 32-channel board obtained input from the pressure transducers and strain gages. An 8-channel board obtained input from the thermocouples.

7.3.4 Test Sequence

The sequence for filling the system and performing the test was important to ensure repeatable, predictable, condensation induced waterhammers. The system was filled and the boiler was brought up to pressure before testing commenced. Additionally, some preliminary tests were run each day before measured testing commenced. The test sequence is described below.

7.3.4.1 Filling

The CIWH test piping was filled and flushed with cold tap water before each test. Filling the system was accomplished by filling the receiver tank through the fill line to a mark on the receiver tank sight glass. Once filled, the receiver tank was pressurized with air through the air supply/vent line to approximately 15 psig. With the receiver tank pressurized, valve V1 and the drain line right underneath V2 were opened, allowing the system to fill and flush. Once the system was sufficiently flushed and the temperature of the water (indicated by the thermocouples) fell below 100°F, the drain lines were closed. During filling and flushing of the system, pressure in the receiver tank was maintained to ensure that the system was water solid. Note that V2 was closed this far.

Before initiation of each test, water was pumped above V2 to ensure that the system was water tight through the valve. Water was pumped above V2 by overcoming the steam pressure and the static head, typically steam pressure plus 3 psig. With sufficient pressure in the receiver tank, V2 was opened and closed once the water level rose to a mark on the sight glass over V2. With the system pressurized, V1 (2" ball valve) was closed. The vent on the receiver tank was opened and the drain line right above V2 was opened until steam was emitted. The system was now filled.

7.3.4.2 Set Test Conditions

The pressure in the LP steam tank was set by adjusting the set pressure for each control valve. This was accomplished by adjusting the valve's spring modulating screw. The 2½" valve was set approximately 1/2 psi above the pressure for the 2" valve. Valve pressure was only adjusted once for each set of tests performed at a particular driving pressure, and it was monitored using the dial pressure gage on the LP tank.

With the system filled and prior to closing V1, two water samples are taken for dissolved oxygen readings, one from a drain tapped into horizontal section of the 4" piping downstream of V2 and the other from a drain in the 2" piping just downstream of the flow meter.

The steam supply was vented for approximately one minute at this point, using the top vent on the 4" steam piping.

Pressure was relieved in the receiver tank. If the receiver tank was to be run at a vacuum, the desired pressure was set by running the vacuum pump.

The globe valve was set to the number of open turns to provide the desired drain rate.

7.3.4.3 Waterhammer Generation

Test initiation and data acquisition begins with the operator starting the control program. The program opens V1 and V2 simultaneously. Steam and water advances down the vertical section on which V2 was installed and steam enters the horizontal section. Steam voids became trapped in the horizontal section and condensation induced waterhammers occur.

Condensation induced waterhammer pressure pulses propagate through the system and are recorded by the pressure transducers installed along the system. Support reactions are recorded by the strain gage installed on the support strut.

7.3.4.4 Test Shut-Down

Test termination was controlled by the control program. The control program closes both ball valves simultaneously approximately 10 to 16 seconds after initiation. Termination time was dependent upon the drain rate. The termination time was set so that steam did not enter the receiver tank.

The test was brought back to the refilling position by breaking the vacuum on the receiver tank and replacing any make-up water in the tank.

7.3.4.5 Dissolved Oxygen Monitoring

Sampling and testing of the level of dissolved oxygen in the test section for the CIWH tests was performed using a nitrogen blanket to prevent contamination of the water sample. To accomplish this, a beaker was filled with nitrogen gas from a gas cylinder. The oxygen meter was switched to measure the dry air quantity of oxygen and the probe was inserted into the beaker. When the amount of oxygen in the beaker was less than 1%, the water sample was drawn into the bottom of the beaker using an extension from the drain. This sample was kept in motion using a magnetic remote stirrer as instructed by the manufacturer of the oxygen meter. The oxygen meter was then switched to measure the dissolved oxygen in the fluid. In this manner, water from the test piping was not inadvertently aerated and an accurate measurement could be made.

7.4 Test Lists

Table 7-1 and Table 7-2 provide a listing of each CIWH test and the conditions for each test. The peak waterhammer pressure measured during each test is also listed. The driving steam used in all of these tests was created from deaerated water. Note that the units for driving steam pressure are psig in the tables and psia on the following plots. This and other test conditions were discussed in Section 7.3.1 of this report.

Table 7-1 is the normal water test list. Table 7-2 is the deaerated water test list.

The Test Name code used in Table 7-1 and Table 7-2 consists of a sequence of items separated by hyphens. In all tables, the first is the driving steam pressure in psig, and the second is the valve position in number of turns from full closed.

In Table 7-1, the third is the test sequence number. All of the tests listed in Table 7-1 were conducted with a receiver tank pressure 18 in-Hg below atmospheric pressure.

In Table 7-2, the third is the receiver tank pressure, either atmospheric or 10 in-Hg below atmospheric pressure. The fourth identifies the location of the pressure transducer. The fifth is the test sequence number.

In Table 7-2, when the sixth to the end term is "D(D_w-4psi-sys)" it means that the water is deaerated and that the system was filled with this water at 4 psig system pressure. When the sixth to the end term is "D-A(D_w-4psi-sys)" in addition to this it means that the test section piping was restrained better in the lateral and vertical directions.

Table 7-1
Normal Water Test List

Table 7-1
Normal Water Test List (Continued)

Table 7-2
Deaerated Water Test List

Table 7-2
Deaerated Water Test List (Continued)

Figure 7-7 through Figure 7-10 show typical results for a test. Figure 7-7 shows the pressure data recorded during the test. Figure 7-8 shows the pressure data on a reduced time scale. It is apparent from Figure 7-8 that there was a minor reduction in steam pressure as the void collapsed. This was typical and indicated that the steam supply pressure was not significantly affected by the condensation. For accurate comparison of the waterhammer magnitude to the actual driving pressure, the driving steam pressure was averaged over the time period corresponding to the void formation and collapse (defined as the time from the minimum pressure to the pulse maximum). This is the "Driving Steam Pressure During Void Collapse" data presented in Figure 7-1 and Figure 7-2 and annotated on Figure 7-8. The steam pressure shown in the plot is in terms of absolute pressure to allow visual differentiation from P1 and P2 which are in gauge pressure. The pulse duration is also annotated on Figure 7-8 and is defined as the time from when the pressure reaches 10% of the maximum pressure and until when the pressure returns to this value.

Figure 7-7
Typical Pressure Test Data Results

Figure 7-8
Typical Pressure Test Data Results – Reduced Time Scale

Figure 7-9
Typical Temperature and Flow Test Data Results

Figure 7-10
Typical Temperature Test Data Results – Reduced Time Scale

Figure 7-9 shows the temperature data recorded during the test as well as the water flow rate. Figure 7-10 shows thermocouples T1 through T4 on a reduced time scale. The sloped, stratified nature of the water/steam interface is apparent by evaluating the time when each transducer sees an increase in temperature.

7.5 Test Results

7.5.1 Pulse Magnitude – Normal Water

The horizontal pipe drain test produced waterhammer pressure pulses that increased with steam driving pressure but were far less than that predicted by an analytical model based on the Joukowski equation and inertia limits for velocity, with conservative values for void fraction α and sonic velocity C. Figure 7-11 shows the peak waterhammer pressure response for normal water, plotted versus steam pressure at the time of void collapse. Also included is a curve representing the analytical model predictions (Equation 7-6, using $\alpha = 0.5$ and $C = 4{,}600$ ft/sec). The predictions from the analytical model are higher due to the conservative test conditions described previously and the use of the Joukowski equation for a relatively short pipe section. The use of an α of 0.5 and a sonic velocity of 4,600 ft/sec are both considered to be conservative. Neither α nor the sonic velocity, particularly local to the collapsing void, are known.

Additional CIWH testing was performed in previous studies [20, 21] using 2" pipe with normal tap water and system pressures of 10 to 20 psia. These results for 2" piping are included in Figure 7-11. Note that the 2" and 4" CIWH testing resulted in similar pulse magnitudes for similar test conditions. This comparison between the 2" and 4" piping data provides a trend that tends to indicate independence of CIWH magnitude and pipe size. Further scaling discussion is provided in Section 7.6.

Figure 7-11
Waterhammer Peak Pressure vs. Driving Steam Pressure – Normal Water

7.5.2 Pulse Duration – Normal Water

The pressure impulse is the pulse magnitude integrated over the duration of the pressure pulse. For a constant steam supply pressure, the area under the pressure-time (*P-T*) curve should be constant. This can be shown as follows:

Pressure Magnitude: $\Delta P = k \cdot \rho \cdot C \cdot \Delta V$

Pulse Duration: $t_d = 2 \cdot L_w / C$

Impulse: $I = \Delta P \cdot t_d$

Substituting $I = k \cdot \rho \cdot C \cdot \Delta V \cdot (2 \cdot L_w / C)$

Simplifying $I = (2 \cdot \rho \cdot (P_o - P_v) \cdot L_{stm} \cdot L_w)^{1/2}$

where L_{stm} is the length of the steam void and L_w is the length of the water column closing the void.

This shows that for a constant driving pressure (P_o - P_v), within the limits of these assumptions, the impulse would be expected to be constant. Substituting values for the test configuration provides an average impulse of [ ] as shown in the following table:

Table 7-3
Calculation of Waterhammer Impulse

Variable	Value to minimize pressure impulse	Value to maximize pressure impulse	Comment
ρ	62 lbm/ft^3	62 lbm/ft^3	Relatively constant
P_o	25 psia	30 psia	Set for each test
P_v	2 psia	1 psia	Approximately P_{sat} for the draining water (85°F)
L_w	[ ]	[ ]	exact length unknown, value approximated from temperature data recorded along length of test section
L_{stm}	[ ]	[ ]	Exact length unknown, higher value approximated from conservative $\alpha = 0.5$
I (Pressure Impulse)	[ ]	[ ]	[ ]

Figure 7-12 presents the normal water drain test peak pressure pulse magnitude data versus the pulse duration. The higher magnitude pulses have shorter pulse durations, and the lower magnitude pulses have longer duration. This is consistent with a constant impulse assumption.

Figure 7-12
Waterhammer Peak Pressure vs. Pulse Duration – Normal Water

Figure 7-12 curve has been developed using the constant impulse theory. For constant impulse, an approximation of the integral is that the peak pressure ΔP times the duration t_d is a constant pressure impulse ($I = \Delta P \cdot t_d$). The pressure impulse of [ ] was selected based on the evaluation in Table 7-3 and compares well with the test data shown in Figure 7-12. The pulse durations of up to 0.25 seconds are relatively long in comparison to pulse durations measured for higher magnitude waterhammers.

7.5.3 Support Loads – Normal Drain

Waterhammer pulse duration is an important factor in the loading of a structure. A classical structural dynamics approach is to determine a dynamic load factor (DLF) based on the ratio of the time loading function to the natural period of the structure. For the relatively long duration pulses produced in the normal water CIWH testing, loads produced by the unbalanced pressure forces in the horizontal run are fully transferred onto the piping structure (DLF = 1.0). The full load is the peak pressure ΔP times the piping cross sectional area A.

Presented in Figure 7-13 are the support loads measured at the end of the horizontal test section plotted versus the peak waterhammer pressure. Figure 7-13 shows that the waterhammer pressure loads transfer to support loads linearly up to a peak waterhammer pressure of approximately 125 psig. The solid line represents the pressure times the pipe cross sectional area of 12.73 in^2 ($\Delta P \times A$) for the 4" schedule 40 pipe used in the test. Above 125 psig, the two data points at 150 psig and 180 psig appear to indicate that as the duration of the pressure pulse becomes smaller, the structure does not fully respond. Figure 7-12 showed that the higher magnitude pulses have briefer durations. Additional data from other tests confirm the trend seen here at higher pressures.

Figure 7-13
Support Load vs. Waterhammer Peak Pressure – Normal Water

7.5.4 Pulse Magnitude – Deaerated Water

The horizontal pipe drain test was also run with deaerated water. This produced waterhammer pressure pulses that were higher than the normal water tests. By comparison to the normal water tests, the increase in pulse magnitudes demonstrates the mitigating influence of air on waterhammer. These waterhammer magnitudes also increased with steam driving pressure but remained less than that predicted by the analytical model based on the Joukowski equation with inertia limits for velocity and conservative values for void fraction α and sonic velocity C. Figure 7-14 shows the peak waterhammer pressure response for both normal and deaerated water, plotted versus steam pressure at the time of void collapse. Figure 7-11 showed a similar plot for the normal water test data only. Also included is a curve representing the analytical model predictions (Equation 7-6, using $\alpha = 0.5$ and $C = 4{,}600$ ft/sec.). This figure demonstrates that the analytical model conservatively over-predicts waterhammer magnitude even for deaerated water conditions and that the presence of air in the water reduces the waterhammer pressure pulse magnitude. Recall that the steam was deaerated in both tests.

7.5.5 Pulse Duration – Deaerated Water

The deaerated water tests produced higher pressure magnitudes than the normal water tests. The high magnitude pulses, however, had very short durations. The relationship between pulse magnitude and duration is presented in Figure 7-15. The data is presented along with the constant impulse curve fit using the same constants as before. The peak pressure ΔP times the duration t_d is the constant pressure impulse ($\Delta P \times t_d = I$ or $\Delta P = I/t_d$) with [...........]. Note that the impulse appears constant for both normal and deaerated water events.

Figure 7-14
Waterhammer Peak Pressure vs. Driving Steam Pressure – Normal and Deaerated Water

Figure 7-15
Waterhammer Peak Pressure vs. Duration – Normal and Deaerated Water

7.5.6 Support Loads – Deaerated Water

Presented in Figure 7-16 are the support loads measured at the end of the test section plotted versus the peak waterhammer pressure for both normal water and deaerated water. Figure 7-16 shows the decrease in the relative force response with waterhammer pressures above approximately 150 psig. The data demonstrates that the relationship of force to waterhammer pressure is far less than linear for higher pressure and shorter duration waterhammer pulses. The line on the figure shows pressure times area for a 4" schedule 40 pipe, which has a cross sectional area of 12.73 in^2. The diminished structural response correlates well with the data presented in Figure 7-15, which shows that the pulse duration decreases as the waterhammer magnitude increases. The pulses become brief relative to the structural response of the piping system, and the resulting support reaction is limited.

Figure 7-16
Support Load vs. Waterhammer Peak Pressure – Normal and Deaerated Water

7.5.7 Waterhammer Pressure Impulse

The waterhammer peak pressure versus duration plots (Figure 7-12 and Figure 7-15) were each plotted with a line that showed the constant pressure impulse relationship between the pressure magnitude and duration. The higher magnitude pulses have very short durations and the low magnitude pulses have longer durations. Pressure impulse was determined from the area under the pressure time curve. The pressure impulse was estimated in Table 7-3. The actual pressure impulse was determined from the normal and deaerated tests and is plotted against waterhammer pressure in Figure 7-17. This figure shows that the estimated pressure impulse of [ ] is conservative for the test data.

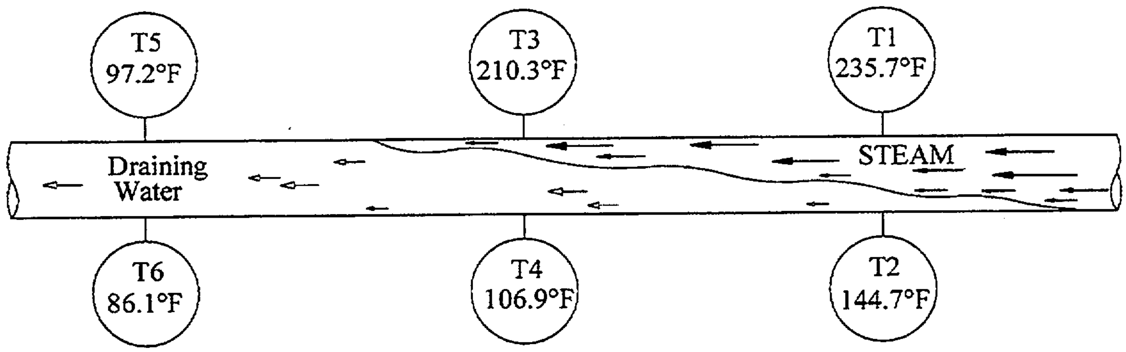
Figure 7-17
Waterhammer Pressure Impulse vs. Waterhammer Peak Pressure

The data shows that while the pressure impulse is relatively constant, the lower magnitude, longer duration pulses that result from the normal water tests tend to have greater pressure impulse as shown above and fall above the constant pressure impulse line of Figure 7-15. The larger impulses combined with the longer pulse durations provide the highest loading to the pipe system and are the most severe. Other waterhammer test data, such as the deaerated tests, have larger pressure magnitude but briefer duration and lower impulse, demonstrated by the data falling below the constant impulse line of Fig 7-15. These pulses therefore provide less loading on the structure and have a generally lower likelihood to cause damage.

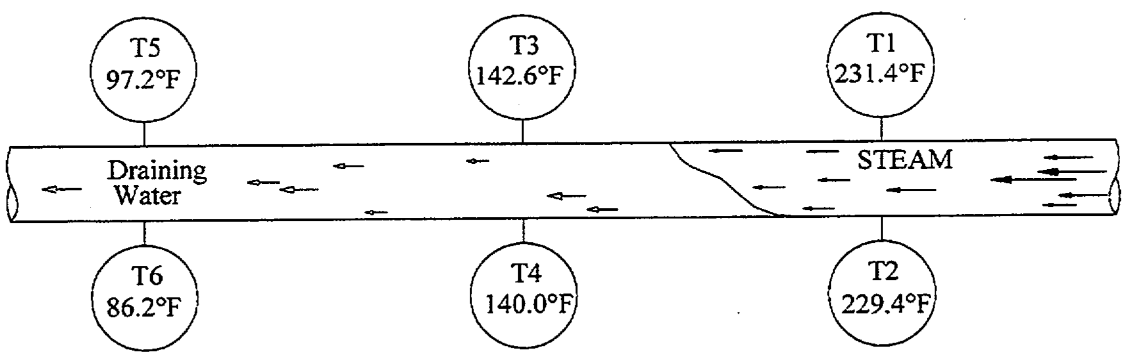
The application of the impulse loading to the piping system can be seen in the Figure 7-13 and Figure 7-16. The higher pressure magnitude pulses (shorter duration, lower impulse) do not fully load the piping structure along the $\Delta P \times A$ line. While this general conclusion will be system specific – as actual piping and support stiffness will affect the precise response, the test configuration was prototypical, and dramatic changes in this conclusion are not expected.

7.5.8 Waterhammer Relation to Drain Rate

An additional area investigated as part of the testing was the relationship between drainage rate and CIWH occurrence. The characteristics of the drainage and the shape of the wave front have been previously investigated [19]. The shape of the water/steam interface was investigated by using fast (0.1 sec) response thermocouples positioned at intervals along the top and bottom of the pipe. The thermocouples penetrated the pipe wall and extended approximately 1/4" to 1/2" into the flow. The thermocouple temperature rose dramatically when the environment transitioned from subcooled water to saturated steam as the thermocouples became uncovered (see Figure 7-9 and Figure 7-10). Comparing the temperature rise time measured by the thermocouples on the pipe to the axial positions of the thermocouples provides indication of the angle of the draining fluid face. This is depicted in Figure 7-18. The temperatures indicated in the thermocouples are for a time slice prior to and following the CIWH. The steam temperature is approximately 240°F and the initial water temperature was approximately 86°F.



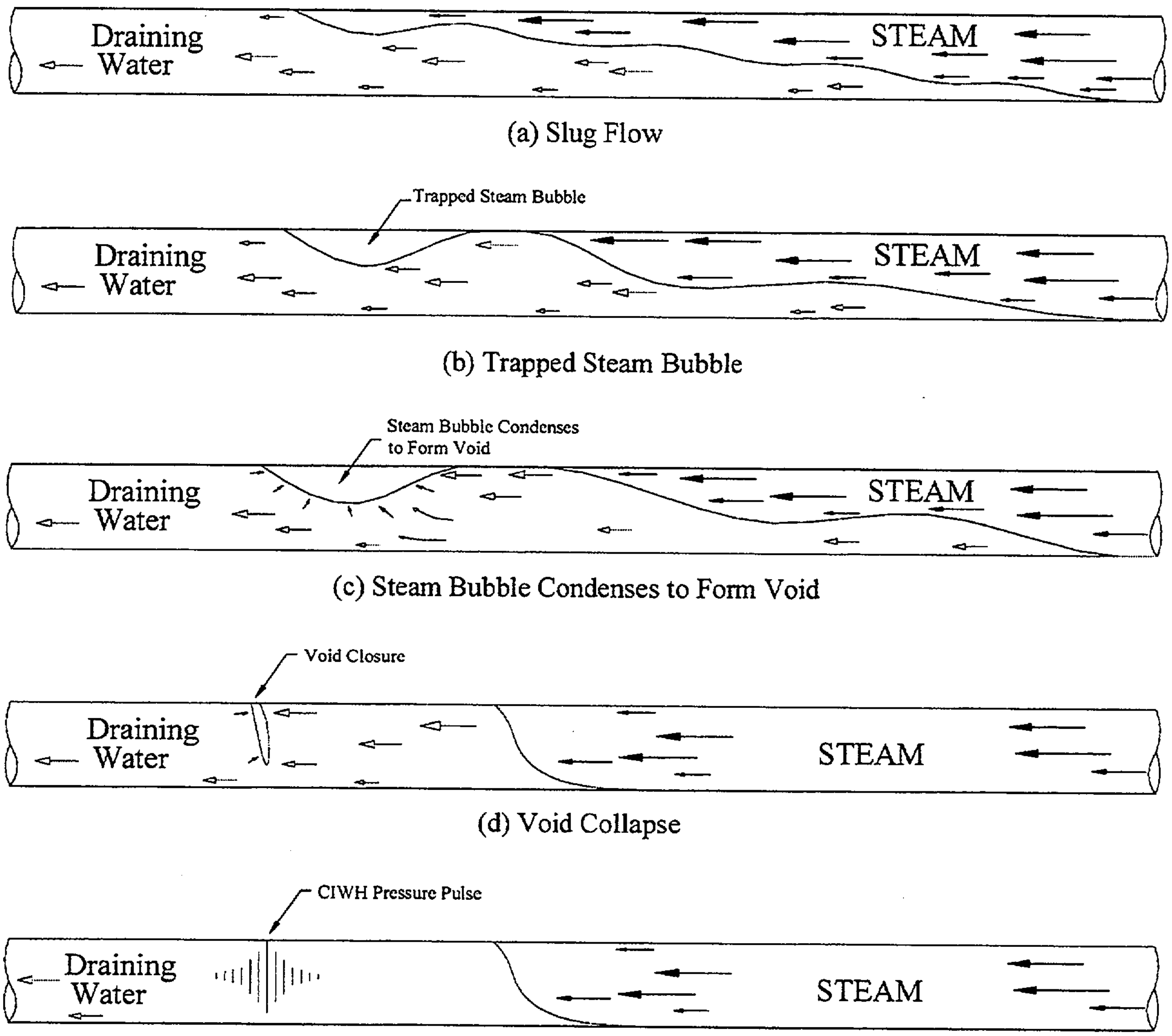
(a) Steam-Water Interface Prior to CIWH Event



(b) Steam-Water Interface After CIWH Event

Figure 7-18
Position of Thermocouples Showing Angle of Voiding Face

It is evident from the temperature traces that the draining flow is never fully stratified along the length of the pipe, nor is the flow pushed down the pipe in a "piston" manner. The water face always drains at an angle during the CIWH tests. Also, based on the test data showing the bottom thermocouples coming up to the steam temperature slower, or reaching an intermediate temperature, it is apparent that the trailing edge of water becomes heated. Most of the condensation is occurring in the upper corner, at the leading edge of the steam tongue that advances along the top of the draining fluid. These effects limit the exposed surface area and amount of condensation, and very likely limit the void fraction at the void closure. The trapped bubble is a result of water being pushed "uphill" by the steam flow across the water surface. The resulting voiding condensation model appears as shown in Figure 7-19.



(a) Slug Flow

(b) Trapped Steam Bubble

(c) Steam Bubble Condenses to Form Void

(d) Void Collapse

(e) CIWH Pressure Pulse

Figure 7-19
Detail of CIWH Event

A plot of the peak waterhammer pressure as a function of the drainage rate is presented in Figure 7-20. The scatter of the data indicates that there is little relation of the waterhammer magnitude to the rate of drainage, expressed as a Froude number.

The pipe drain rate does affect the number of waterhammers that occur along the test section. The process is such that the sloped steam water interface forms, traps a bubble, collapses to produce a waterhammer, and then starts forming again. At lower drainage rates, this cycle can occur more times for a given length of pipe before the pipe is completely drained. Multiple waterhammers were noted in the testing performed. The magnitudes were all similar. This indicates that, beyond a minimum pipe length required to get CIWH to occur, the waterhammer magnitudes are independent of the length of the horizontal pipe.

Figure 7-20
CIWH Pressure vs. Draining Rate – Normal and Deaerated Water

7.6 Scaling

The general system consists of a horizontal pipe, partly filled with steam and non-condensable gas, bounded by water columns at each end. Steam condensation occurs on one or both liquid interfaces, which may be flowing and draining at the same time. Gravity causes the interface to spread, much like the profile of a classical dam break problem. Either one or both water columns are pulled together by the decreasing pressure as steam is condensed in the void.

The experiments in the 4" pipes were compared to similar testing in 2" pipes to measure waterhammer pressures that would be representative of full size CIWH, or that would provide conservative results to be employed in full size systems. The draining water interfacial area on which condensation occurs grows on a different time scale (Froude) than the acceleration of a water column to impact. This feature of the tests is likely to cause higher-than-representative interface condensation, lower void closing pressures, and higher impact velocities than would be expected in larger pipes.

The following discussion shows that for smaller pipe sizes, which do not introduce significant surface tension and viscous effects, experimental column impact velocities also would be higher than expected in full size piping. Even though the void pressure prior to impact is expected to be lower, the absolute impact pressure in the tested pipes would be larger than impact pressures in larger pipes.

7.6.1 Segment Scaling of CIWH

The CIWH tests were performed in pipes of smaller diameter than in full size systems, but with the pipe and water column length preserved 1:1. Furthermore, the experiments were designed to closely preserve full size water column velocities and thermodynamic state and transport properties. This scaling approach is known as "segment scaling" since it can be interpreted as a small cross-section tube or segment of water and voids, with full size length, removed from a large pipe of water and voids. Pressure and velocity behavior in any one such tube would be identical to the full size pipe system. However, phenomena that are dominated by Froude scaling, such as the water interface drain rate, are not preserved in this kind of segment scaling.

7.6.2 Pressure Rate in the Void

If the void is treated as a uniform mixture of vapor and a small amount of non-condensable gas, the pressure rate, caused by heat transfer and condensation on the water interface, and by the volume change of the void itself, is given by

$$\frac{dP}{dt}=\frac{-\left(h_f(P)-F_1(P)\right)\cdot m'_{gf}-q-\left(P+\left(\frac{\partial e}{\partial v}\right)_P\right)\cdot\frac{d\forall}{dt}}{\rho\cdot\forall\cdot F_2(P,v)} \qquad \text{7-8}$$

The functions $F_1(P)$ and $F_2(P,v)$ are given by

$$F_1(P)=e-v\cdot\left(\frac{\partial e}{\partial v}\right)_P \qquad \text{7-9}$$

and

$$F_2(P,v)=\left(\frac{\partial e}{\partial P}\right)_v \qquad \text{7-10}$$

Also, m'_{gf} is the condensation rate, which removes steam at specific enthalpy h_f, q is the heat transfer rate to the draining water interface, and $\forall$ is the void volume.

Thermodynamic properties ρ, $F_1(P)$, $F_2(P,v)$, and $(\partial e/\partial v)_P$ are to be preserved 1:1. Since heat transfer to the water interface removes the heat of condensation from saturated vapor in the void, the condensation rate is expressed as:

$$m'_{gf}=\frac{q}{h_{fg}} \qquad \text{7-11}$$

Equation 7-8 can be written as

$$\frac{dP}{dt} = -F_3(P,v)\cdot\frac{q}{\forall} - F_4(P,v)\cdot\frac{q}{\forall}\cdot\frac{d\forall}{dt} \tag{7-12}$$

Where F_3 and F_4 are the combined thermodynamic properties,

$$F_3(P,v) = \frac{(h_g - f)\cdot v}{h_{fg}\cdot F_2(P,v)} \tag{7-13}$$

And

$$F_4(P,v) = \frac{\left(P + \left(\frac{\partial e}{\partial v}\right)_P\right)\cdot v}{F_2(P,v)} \tag{7-14}$$

If the void pressure-time response of Equation 7-12 is to be preserved between small and large pipes, the coefficients of F_3 and F_4 should have no dependence on pipe diameter.

7.6.3 Scale Distortion

The void volume can be expressed by:

$$\forall = A\cdot z(t) \tag{7-15}$$

where A is the pipe flow area, and $z(t)$ is the collapsing void length. Therefore, the coefficient of F_2 is given by

$$\frac{1}{\forall}\frac{d\forall}{dt} = \frac{1}{z(t)}\frac{dz}{dt} = \frac{1}{z(t)}V \tag{7-16}$$

where V is the void closure velocity. Equation 7-16 contains no dependence on pipe diameter, since the void closure velocity and length are to be segment-scaled 1:1.

The coefficient of F_1 is considered next. First, the heat transfer rate is given by

$$q = h\cdot A_{cds}(t)\cdot\Delta T \tag{7-17}$$

where h is the condensation heat transfer coefficient, $A_{cds}(t)$ is the draining water interface area, and ΔT is the vapor-liquid temperature difference. The interface area will grow according to Froude scaling, for which its length in the flow direction extends at a rate proportional to $\sqrt{gD}$, and its width is proportional to the pipe diameter D. Therefore, if the interface area is initially equal to the pipe flow area, it grows as

$$A_{cds}(t) \approx A + b \cdot D \cdot \sqrt{gD} \cdot t \qquad \text{7-18}$$

where b is a constant. Noting that $A = \pi D^2/4$, the coefficient $q/\forall$ becomes:

$$\frac{q}{\forall} = h \cdot \Delta T \cdot \frac{1}{z(t)} \cdot \left(1 + B \cdot \frac{t}{\sqrt{D}}\right) \qquad \text{7-19}$$

where B is another constant. If h and ΔT are approximately preserved, like the other thermodynamic properties, it is seen from Equation 7-19 that $q/\forall$ does have a dependence on pipe diameter D, which causes a distortion in the scaling.

7.6.4 The Effect of Scaling Distortion

The segment-scaled experiments would ideally preserve the water column velocity, the composition of the steam/air mixture, and the void pressure, producing representative waterhammer pressures at impact. However, Equation 7-19 shows that the $q/\forall$ term does depend on the pipe diameter, and tends to become larger for smaller diameter pipes. It follows from Equation 7-12 and Equation 7-19 that *smaller* diameter pipes will have *higher* void decompression rates. This means that at any time during void condensation collapse and water column acceleration, the void pressure P_v will be *lower* in smaller pipes than it would be in larger pipes. A lower void pressure would cause a *higher* water column velocity at impact, resulting in *higher* waterhammer impact pressure rise in smaller pipes, since waterhammer pressure is related to the impact velocity by

$$\Delta P \propto \rho \cdot C \cdot V \qquad \text{7-20}$$

Since the void pressure P_v would be lower in smaller pipes and the impact pressure of Equation 7-21 would be higher, it is not obvious whether the absolute impact pressure would be higher or lower in smaller pipes. However, since the velocity of a finite water column is proportional to the driving pressure difference, $(P_o - P_v)$, the absolute impact pressure can be expressed as

$$P_1 = P_v + \Delta P = P_v + F(P_o - P_v) \qquad \text{7-21}$$

As pressure P_v is decreased in smaller pipes, the absolute impact pressure increases. This can be seen by noting the limits on the void pressure P_v. If $P_v = 0$, the water column velocity is maximum, and the impact pressure P_I reaches the full waterhammer value. If $P_v = P_o$, there is no driving force on the water column, whose velocity would be zero, and the impact pressure of Equation 7-21 would remain at P_o. Therefore, both the waterhammer pressure rise and the absolute impact pressure in the smaller experimental pipes would be higher than expected in larger pipes.

7.7 Results of Tests and Evaluation

Given a constant pressure impulse relationship between the pressure magnitude and pulse duration, the higher pressures noted in some tests are of little consequence to piping systems. Referring primarily to Figure 7-12 and Figure 7-15, it can be seen that the high magnitude pulses have durations less than 0.025 seconds. When compared to the natural periods for typical piping systems, the low duration, higher magnitude pulses are less significant than the lower magnitude, longer duration pulses.

For a structure responding to a short duration load, the peak response can be calculated by comparing the forcing function frequency with the natural frequency of the structure. Using a classic single degree of freedom model and triangular shape loading for the pressure pulse, the peak response is at approximately 0.8 times the period of the structure [22]. Using a stiff piping system with response frequencies on the order of 40 Hz, the peak response for a triangular pulse will occur at 0.8 times this value or 32 Hz. The duration of the triangular pulse that provides the largest structural reaction is:

$$T = 1/fr = 1/(32\text{ Hz}) = 0.0313\text{ sec}$$

Figure 7-15 can be used to determine the CIWH pressure that corresponds to the most severe structural loading for a 40-Hz system. Using the "constant impulse, [ ]" curve to represent the pressure duration relationship in Figure 7-15, the pressure at this duration can be calculated by the following equation:

$$\Delta P = I/t_d = [\quad]$$

For a time duration of 0.0313, the pressure is calculated as:

$$\Delta P = [\quad]/0.0313 = [\quad]$$

This means that a [ ]-second duration pulse represents the most severe pressure pulse for loading the structure. Higher magnitude pulses will have a reduced effect on the structure due to their shorter duration times. Longer duration pulses will have lower pressure magnitudes and will also have a reduced effect on the supports. Although this relationship is non-linear, it is clear that there is a limit on the maximum effective pressure due to impulse limits.

This effect can be seen in Figure 7-16. The piping force response data falls below ~ 2,500 lbf, regardless of waterhammer pressure. The high pressure, low duration events load the structure well below the $\Delta P \times A$ line. The longer duration, lower duration events load the structure as shown on the $\Delta P \times A$ line, but still below the 2,500-lbf level. If the 2,500-lbf reaction is used as the maximum response along the $\Delta P \times A$ line, this corresponds to a pressure pulse of 195 psig.

Based on the test results and the above discussion, it is clear that CIWH pressure loads, in a low pressure system with limited pressure impulse, do not significantly affect the piping structure beyond the 150 psi to 200 psi range for very conservative, deaerated water conditions and less than 100 psi for prototypical water conditions.

7.8 Comparison to Column Closure Waterhammer

As a comparison between CIWH and column closure waterhammer (CCWH) for the conditions typical of the low pressure service water systems that are the subject of GL96-06, the following statements can be made:

- CCWH are produced by closure velocities of 10-20 ft/sec. Waterhammer magnitudes are expected to be between approximately 300 and 600 psig.
- A pumped SW system will have a substantial column of water closing the void. Column lengths from the pumps or from a large header to the void closure location are expected to be 100 to 400 feet.
- The pressure impulse produced by these CCWH events will be 13 to 107 psi·sec.
- The pressure impulse for the CCWH will be between 3 and 24 times greater than the pressure impulse for a CIWH in a low pressure (20 psig or less) system. Therefore, the CIWH event will not provide as severe a loading condition as the CCWH event.

7.9 Conclusions for CIWH

CIWH tests were performed with both normally aerated and deaerated water, and conservatively simulating no thermal layer, no air in the steam, and with a steam driving pressure that is higher than is expected in most plants.

The characteristics of the waterhammers measured in the tests include the following:

- The peak pressures for the normally aerated water pipe tests were all less than 180 psig.
- Waterhammer occurrences follow a constant pressure impulse behavior for a specific set of conditions.
- The constant impulse behavior is not affected by air content.
- The system response is proportional to the loading produced by the maximum pressure times the pipe cross sectional area ($\Delta P \times A$) for pulse durations that are greater than the natural period of the system. These pulses tend to be long, low magnitude waterhammers. Higher magnitude pulses are too brief to fully excite the system and produce less than $\Delta P \times A$ response.
- Waterhammer pressures are independent of draining Froude number.
- Waterhammer pressures are independent of pipe length.

A scaling evaluation of the testing program concluded that both the waterhammer pressure rise and the absolute impact pressure in the smaller experimental pipes would be higher than expected in larger pipes.

7.10 Recommendations

Recommended practices are described in the User's Manual in Section 4.2. The recommendation provided there states CIWH that may occur in low pressure service water systems are limited in magnitude and/or duration and are not a credible threat to pressure boundary integrity. This conclusion is applicable only in systems that meet the following conditions:

- the system steam pressure at the time of the postulated CIWH is less than 20 psig
- the piping has been shown by test or analysis to be capable of withstanding a CCWH following LOOP, LOOP/LOCA, or LOOP/MSLB

If these conditions are met, explicit calculation of CIWH magnitude is not required. If these conditions are not met, explicit calculation of CIWH magnitude will be required. Explicit methods for such calculation are not provided herein.