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Evaluation of Water Hammer Events in Light Water Reactor Plants

Prepared by R. A. Uffer, S. Banerjee, F. B. Buckholz, M. Frankel,
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Quadrex Corporation

EG&G Idaho, Inc.

Prepared for
U.S. Nuclear Regulatory
Commission

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FOREWORD

PREPARED BY THE NRC STAFF

This report presents the results of evaluations of reported water hammer occurances in nuclear power plants performed by the Quadex Corporation for EG&G, Idaho as part of NRC's technical efforts related to the resolution of the unresolved safety issue (USI)A-1, water hammer. The findings and recommendations set forth in this report are those of the contractor and will be reviewed and considered by the NRC staff in its development of a technical resolution position for USI A-1.

ABSTRACT

This document presents the results of an evaluation of water hammer events in LWR power plants. The evaluation was based upon reports of actual events, typical plant design drawings and operating procedures. Included in this report are design and operating recommendations for the prevention or mitigation of water hammer occurrence.

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NOMENCLATURE

Acronyms

ADS	Automatic Depressurization System
AE	Architect/Engineer
AFW	Auxiliary Feedwater
ANSI	American National Standard Institute
ASME	American Society of Mechanical Engineers
B&W	Babcock and Wilcox
BTP	Branch Technical Position
BWR	Boiling Water Reactor
CCW	Component Cooling Water
CE	Combustion Engineering
CS	Core Spray
CST	Condensate Storage Tank
CV	Control Valve
CVCS	Chemical and Volume Control System
ECCS	Emergency Core Cooling System
EECW	Emergency Equipment Cooling Water
EHC	Electro-Hydraulic Control
EPRI	Electric Power Research Institute
FW	Feedwater
FBV	Feedwater Bypass Valve
FCV	Feedwater (or Flow) Control Valve
FSAR	Final Safety Analysis Report
GE	General Electric
HHSI	High Head Safety Injection
HPCI	High-Pressure Coolant Injection
HPCS	High-Pressure Core Spray
Hx	Heat Exchanger
IE	Inspection and Enforcement
LER	Licensee Event Report
LHSI	Low Head Safety Injection
LOCA	Loss-of-Coolant Accident
LPCI	Low-Pressure Coolant Injection
LPCS	Low-Pressure Core Spray
LWR	Light Water Reactor
MS	Main Steam
MSIV	Main Steam Isolation Valve
MWe	Megawatt electric
MWt	Megawatt thermal
NPSH	Net Positive Suction Head
NRC	Nuclear Regulatory Commission
NSSS	Nuclear Steam Supply System
NUREG	Nuclear Regulation
P&ID	Piping and Instrumentation Diagram
PWR	Pressurized Water Reactor
QA	Quality Assurance
RCIC	Reactor Core Isolation Cooling
RCP	Reactor Coolant Pump
RCS	Reactor Coolant System
RHR	Residual Heat Removal
RHx	Regenerative Heat Exchanger
RPV	Reactor Pressure Vessel

NOMENCLATURE

Acronyms

RV	Reactor Vessel
RW	Reactor Water
RWST	Refueling Water Storage Tank
RWCU	Reactor Water Cleanup
SCW	Service Cooling Water
SEP	Systematic Evaluation Program
SG	Steam Generator
SGB	Steam Generator Blowdown
SGWH	Steam Generator Water Hammer
SI	Safety Injection
SIS	Safety Injection System
SRP	Standard Review Plan
SRV	Safety/Relief Valve
TCV	Temperature Control Valve
TMI	Three Mile Island
TSV	Turbine Stop Valve
USI	Unresolved Safety Issue
W	Westinghouse

1.0 INTRODUCTION

This report presents the results of an evaluation of actual and potential water hammer events occurring in LWR power plants. The evaluation was performed by Quadrex Corporation for EG&G, Idaho, Incorporated, and is an extension of previous evaluations by EG&G, Idaho.

Water hammer is the change in the pressure of a fluid in a closed conduit caused by a change in the fluid velocity. The pressure changes can create loads on piping and components.

The occurrence of numerous water hammer events in nuclear power plants led to water hammer being identified as Unresolved Safety Issue (USI) A-1 by the NRC. The objectives of the work reported herein are to evaluate water hammer events that have occurred in commercial nuclear reactors and to develop methods for their prevention and mitigation, as part of an ongoing effort to resolve USI A-1.

Evaluations are based on the incident reports contained in reference 1, reviews of licensee event reports (LERs), FSARs, typical plant design drawings, system descriptions and operating instructions, and the operating and design experience of the authors. Event numbers used in this report are the same as those used in reference 1.

Steam generator water hammers are not included in the scope of this study because they are the subject of other studies.

A summary of the findings and recommendation of this study is presented in section 2.0. Section 3.0 contains generic and overview findings, evaluations and recommendations, based on the individual system evaluations. Individual system evaluations are contained in sections 4.0 and 5.0, for BWR and PWR systems, respectively. Section 6.0 presents recommended mechanisms and regulatory concerns for the prevention and mitigation of water hammer events.

2.0 SUMMARY

An evaluation of water hammers occurring in light water reactor plants was performed using the nonsteam-generator water hammer events listed in reference 1 as a basis. Recommendations for the mitigation or prevention of water hammers were developed.

Implementation of the recommendations contained in this report should resolve water hammer as a safety issue.

This study's evaluations of damage from and the safety implications of water hammer events indicate that water hammer is not as severe a problem as had been originally believed, for the following reasons:

a. Water hammer damage for most of the reported events was limited to the plant piping support systems.

b. Many of the events were either not water hammers or occurred in nonsafety-related systems.

c. Design modifications have already been implemented that have significantly reduced the number of water hammer events in many systems.

The frequency and severity of water hammer events in PWR plants is low. None of the 40 nonsteam-generator events reported in PWR plants disabled a safety system or train, had an adverse safety effect on the plant, or placed a plant in a faulted or emergency condition.

The frequency and severity of water hammer events in BWR plants is higher than in PWR plants. Eighteen of the reported 81 events in BWR plants disabled a safety system train. However, no event disabled more than one train or system, with the possible exception of two flooding events caused by water hammer in a nonsafety system. No event placed a plant in a faulted or emergency condition.

The predominant cause of water hammer events was the presence of voids (gas or steam) in the pumped water lines of both BWR and PWR plants. The presence of these voids was not readily detectable by plant operators. Other major causes of water hammer events were water entrainment in the HPCI turbine inlet and outlet lines and in the isolation condenser inlet lines, and PWR feedwater control valves that were improperly matched with their systems. The causes of several events were unknown. The damage from several events was the result of inadequate support design for loads resulting from anticipated valve-closure-induced steam hammers or safety/relief valve discharges. A detailed overview and generic evaluations of water hammer are presented in section 3.0.

Recommendations for prevention or mitigation of water hammer events fall into two groups. The first group includes recommendations, often peculiar to a particular system or problem, that should not be regarded as regulatory concerns, but rather as suggestions to aid in prevention or mitigation. These recommendations are presented in the generic evaluation of section 3.0 and the individual system evaluations contained in sections 4.0

and 5.0. The second group of recommendations contains those deemed significant enough to warrant regulatory review and possible action. They are presented in section 6.0 and include:

- Void detection, and keep full and venting provisions for several systems. A keep-full system is a system designed to keep a normally idle line full of water.
- Operator training
- Feedwater control valve design verification
- HPCI turbine steam supply line valve control features
- HPCI turbine steam supply line drain pot level detection
- HPCI and RCIC turbine exhaust line vacuum breakers
- Main steam and PWR Reactor Coolant System support and component design basis.

It is recommended that any regulatory requirements be implemented by an SRP or Branch Technical Position for plants in the design phase and by a generic letter for operating plants.

3.0 GENERIC EVALUATIONS

This section contains generic evaluations of water hammer events and their causes, and recommendations of measures for their mitigation and prevention. The findings in this section are based on the individual system evaluations contained in sections 4.0 and 5.0.

3.1 Definition of Water Hammer

The definitions of water hammer types listed below are used in this document.

a. Water (Steam) Hammer. Water (steam) hammer is the change in the pressure of a fluid in a closed conduit caused by a change in the fluid velocity. This pressure change is the result of the conversion of kinetic energy into pressure (compression waves) or the conversion of pressure into kinetic energy (rarefaction waves).

b. Anticipated Water Hammer. An anticipated water or steam hammer is one resulting from a component performing in the manner for which it has been designed and affecting the system in its expected manner. The pressure waves resulting from turbine stop-valve closure are an example of an anticipated event.

c. Unanticipated Water Hammer. An unanticipated water or steam hammer is one that would not be expected from a component or system operating in the manner for which it was designed.

d. Non-Water-Hammer Hydraulic Transients. Hydraulic transients that do not conform to definition a. above are not considered to be water hammers. Examples of non-water-hammer transients are steady-state pipe vibrations or oscillations, normal pressure transients, pump instabilities, and normal safety/relief valve discharge forces.

3.2 Event Summary

3.2.1 PWR Systems

Forty PWR nonsteam-generator water hammer events were reported in reference 1. None had any adverse safety effect on the plant. No water hammer event rendered a safety-related system inoperable or damaged the integrity of the reactor coolant boundary. In most of the events, damage was limited to the piping support system.

The frequency and severity of safety-related water hammer events in the PWR systems are low, with the exceptions of steam generator water hammers, which are not within the scope of this study, and feedwater-control-valve-induced water hammers, which are discussed in section 5.1.

Of the 40 reported events, 24 are considered to be unanticipated safety-related water hammer events. The other 16 events are summarized below.

System (Section)	Number of Events	Remarks
Feedwater (5.1)	1	Neither water hammer nor safety-related
Reactor coolant (5.2)	3	Relief valve discharge reaction forces
Reactor coolant (5.2)	2	Not water hammer (stuck open relief valve)
Main steam (5.3)	4	Anticipated steam hammer
Main steam (5.3)	1	Relief valve discharge reactor force
Condenser (5.7)	3	Not safety-related; jet impingement force event, not water hammer
Condenser (5.7)	1	Not safety-related
Cooling water (5.8)	1	Neither water hammer nor safety-related (in circulating water system)
	16	

Of the 24 safety-related water hammers, 12 occurred in the feedwater system, as shown in section 5.1. Eight of the feedwater system water hammers were related to the feedwater control valve. One other event was due to an improper procedure in opening a valve and another was due to a design error. The cause of two of the feedwater events were unknown. The damage reports indicate that the greatest water hammer forces were generated by events occurring in the feedwater system. This is to be expected due to the large line size, the high fluid velocities and high fluid density in the feedwater system. The feedwater system, especially the design of the FCV, warrants regulatory review and possible action.

A summary of the 24 PWR safety-related water event causes is presented below:

o	Feedwater control valve related	8
o	Line voiding	7
o	*Unknown	5
o	Improper valve usage	2
o	Drain malfunction	1
o	Design error	1
		24

Recommended regulatory review and possible action to address feedwater control valve design (eight events), line voiding (seven events) and operator training (two valve-usage and perhaps the unknown events) is discussed in section 6.3.

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*Of the five events with unknown causes, two in the CVCS system may not have been water hammer and were of low safety significance. Another event in the steam generator blowdown line is of low safety significance.

3.2.2 BWR Systems

The frequency and severity of safety-related water hammer events in the BWR systems are moderate and are greater than for PWR systems.

There were 81 BWR water hammer events reported in reference 1. None of the water hammer events placed a plant in a faulted or emergency condition. However, 18 of the water hammer events rendered a safety system or train inoperable. These included two events where flooding caused by nonsafety-related water hammers rendered safety systems inoperable.

No events damaged the integrity of the reactor coolant boundary. For most of the events, damage was limited to the piping support system.

Of the 81 reported events, 69 are considered to be unanticipated safety-related water hammer events. The 12 other events are summarized below.

System (Section)	Number of Events	Remarks
RCIC (4.5)	1	Not water hammer, probably pump cavitation
Main steam (4.6)	2	Anticipated steam hammer
Main steam (4.6)	1	Relief valve discharge
Main steam (4.6)	1	Not safety-related (in bypass header at condenser)
RWCU (4.8)	1	Not safety-related
Condenser (4.9)	3	Not safety-related
Cooling water (4.10)	2	Not in safety-related systems
Process steam (4.11)	1	Not safety-related
	12	

Fifty-nine of the 69 safety-related water hammer events occurred in four systems, namely, RHR (23), HPCI (20), core spray (9) and service cooling water (7). Therefore, these systems require special attention. Other systems in which safety-related water hammer events occurred include isolation condenser (four), RCIC (one), main steam (two), and feedwater (three).

The most serious BWR water hammer concern is line voiding. It was the largest single cause of BWR water hammers and was responsible for at least 39 events. This generic cause includes flow into voided line, steam-bubble collapse, and possibly some of the unknown events. A generic discussion of line voiding is provided in section 3.3.

Line voiding warrants regulatory review and possible action. Void indication and alarm provisions would essentially eliminate these water hammers (as discussed in section 3.3). If voids are present, the system would then be considered inoperable for technical specification purposes, but would still be available for emergency use.

Other causes of safety-related water hammer in BWR systems are presented below:

o	HPCI turbine steam line drain pot failure	7
o	HPCI turbine exhaust line steam-bubble collapse and water entrainment	7
o	Improper HPCI turbine steam line warm-up	5
o	Improper main steam line warm-up	1
o	Feedwater valve controller instability	3
o	Reactor water entering isolation condenser	3
o	Improper line slope	2
o	Unknown and miscellaneous	2

Certain design modifications and increased operator training would eliminate or greatly reduce the various turbine steam line water hammers (see section 3.5).

3.3 Line Voiding

This section discusses line voiding in both BWR and PWR plants. Line voiding has been identified as the single greatest cause of water hammer events in this report. Forty-nine percent (46 of 93) of the unanticipated safety-related water hammer events reported in reference 1 were caused by pumping water into a line containing voids. Voids can occur through many means, including improper line filling during maintenance, gas evolvement, improper venting, out-leakage of water, in-leakage of steam, and column separation following pump stoppage or valve closure. The generic line-voiding causes discussed in this section include flow into voided lines, steam-bubble collapse and, possibly, some of the unknown events. The one common denominator in each case is that the event could have been avoided had the operator been aware of the void.

Generally, voiding occurs in standby systems that are normally idle. Systems that are continually operating, such as feedwater, are started slowly and kept full by continuous operation. BWR systems are more prone to voiding than similar PWR systems. There are two main reasons for the differences between the BWR and PWR voiding frequency. The first is the elevation of the safety system's water source. The PWR pumps are supplied by the refueling water storage tank, which is maintained at an elevation above the pump discharge lines. The BWR safety systems most prone to line voiding, RHR and core spray, receive their supply from the suppression pool, which is maintained at a level below the elevation of the pump discharge lines. This elevation difference permits line leakage to the suppression pool. Other systems which experience less voiding are supplied by the condensate storage tank, which in many plants is maintained at a level above the pump discharge lines. The open service water systems for both BWR and PWR plants are supplied by sources below the level of the system lines. The second difference between BWR and PWR plants is the presence of steam water interfaces in BWRs. These interfaces can permit the leakage of steam bubbles into low-pressure water lines. The steam replaces water, forming bubbles in the lines.

The comparative studies of the HPCI, RCIC, and AFW systems (section 3.4) indicate that line size is a factor in line voiding and its effects. Smaller lines appear to be less prone to observable water hammer than larger lines. This might be due to the fact that less leakage occurs through the valves of smaller lines. Another factor is that forces resulting from water hammers in small lines are smaller than those resulting from larger lines. Thus water hammers occurring in smaller lines may not be considered reportable, or even detected, if no damage occurred.

The addition of keep-full systems to BWR systems has reduced the frequency of water hammers. (The water supply system for a PWR essentially acts as a keep-full system.) However, venting is also required to remove voids. In many plants, venting is a difficult procedure because of the location of the vent valve. Venting may require wearing anticontamination clothing, entry into moderate radiation areas, considerable climbing and personal discomfort. Operations involving such difficulties are generally performed only to meet specific requirements or needs rather than routinely and frequently.

Certain safety systems may be more prone to water hammer under unplanned (i.e., accident condition) actuation than the reported data indicates. These systems are often vented prior to planned periodic testing or other usage to eliminate voids. An unanticipated start, such as would occur following a postulated accident, may occur with voids in lines and result in a water hammer. Current designs do not provide the operator with information concerning the existence of voids.

Void-caused water hammers can be greatly reduced or eliminated by the use of void detection and alarm, keep-full, and modified venting systems.

3.4 Comparison of HPCI to RCIC and AFW Systems

This section compares HPCI (BWR) with RCIC (BWR) and AFW (PWR) systems to determine causes for the high frequency of water hammer events in the HPCI system. The RCIC and AFW systems are approximately one-tenth the size of the HPCI system, but are similiar in the following respects:

a. The system pumps are driven by steam turbines that are normally in a standby condition.

b. The systems are infrequently used.

c. The systems are surveillance-tested monthly.

d. The systems pump ambient-temperature water through normally unused lines to the feedwater lines at feedwater pressure.

Twenty water hammer events were noted in HPCI systems, compared to only one in an AFW system and one in a RCIC system.

3.4.1 Steam Supply Lines

The supply lines for all three systems are normally filled with steam up to the turbine stop valve and contain steam traps and drain pots. No steam supply line events were noted in either an AFW or RCIC system. Nine steam supply incidents were noted in HPCI systems, four caused by valve operation and five caused by the failure of the steam trap level control and drain system.

There are two significant differences between the HPCI steam supply lines and the RCIC and AFW steam supply lines. The first is the presence of a seal-in control feature on the HPCI outboard isolation valve. A seal-in control feature causes a valve to open continuously to the full open position upon actuation. This feature precludes using this valve for gradual line warmup or venting. The RCIC and AFW isolation valves generally do not have the seal-in control feature.

The second significant difference is size. HPCI lines are sized for approximately ten times the flow rate as AFW and RCIC lines. HPCI lines thus are subject to considerably more steam condensation than AFW and RCIC lines. It is possible that the drain pots of AFW and RCIC systems have sufficient capacity to accommodate occasional malfunctions of the drain systems that may occur between periodic technical specification testing. Water hammer forces are also larger in a larger line. The events in HPCI lines have only caused minor damage. If these events had been scaled down by the 10:1 ratio of the HPCI to the RCIC and AFW systems, their effects may have gone unnoticed and thus unreported.

3.4.2 Steam Exhaust Lines

There were six events reported in HPCI steam exhaust turbine lines and only one in RCIC and one in AFW lines.

HPCI and RCIC turbine exhaust lines discharge into a water interface (the suppression pool), but AFW lines discharge into a gaseous atmosphere. Many of the HPCI events and the RCIC event occurred prior to the addition of vacuum breakers to the exhaust lines. The vacuum breakers prevent a vacuum from drawing suppression-pool water into the lines. The HPCI lines are sized for ten times the flow rate of the AFW and RCIC lines.

The reasons for the higher frequency of HPCI events may be the system's larger size and the presence of the water-steam interface without vacuum breakers in some early installations.

3.4.3 Pump Discharge Lines

Four water hammer events were noted in HPCI pump discharge lines, but none were noted in either RCIC or AFW pump discharge lines.

HPCI and RCIC lines are similar, except that HPCI lines are larger (10:1 flow area) and often longer. Both pumps are normally aligned to the condensate storage tank for suction, and in the systems reviewed discharge to the feedwater lines. AFW lines are approximately the same size as RCIC lines, are aligned to the refueling water storage tank and discharge into the feedwater lines. A more detailed discussion of line voiding is provided in section 3.3.

3.4.4 Conclusions of Comparisons

Although there are several features that distinguish the HPCI system from the RCIC and AFW system, the difference that occurs in all three line types (turbine inlet, turbine exhaust and pump lines) is size. Larger lines may have a greater propensity for condensation (steam lines) and leakage-caused voiding (water lines), which makes them more susceptible to water hammers. Water hammer forces and damage increase with line size. Therefore, smaller water hammers occurring in the RCIC and AFW system may not be significant and thus neither detected nor reported.

3.5 Mitigation or Prevention of Water Hammer

This section provides a discussion of various generic methods recommended to mitigate or prevent water hammer events. The inclusion of a method in this section does not imply that it should be either mandatory for any system or applied to all systems. The measures recommended as warranting review and possible regulatory action along with potential means for their implementation are discussed in section 6.0.

3.5.1 Line Void Detection, Filling and Venting

Forty-nine percent of the safety-related water hammer events reported in reference 1 occurred because water was pumped into a line that contained voids. These events were primarily caused by flow into voided lines, but also included steam bubble collapse. (See section 3.3 for further discussion of voiding.) All these events could have been prevented if the operators had been aware of the existence of the void. A properly designed void detection and alarm system, combined with a technical specification requirement that the voids be corrected, would have prevented these events. The installation of a system to detect the presence of voids at line high points is feasible and can be accomplished with minimal impact on the existing designs. It is difficult to quantify an acceptable void size. Therefore, it is desirable that the void detection system be able to detect the incipience of voiding. Such a system would permit the correction of voids before they reach a significant size. The following systems should have void detection and alarm:

- BWR:
  - Core spray (pump discharge)
  - RHR (all liquid lines)
  - HPCI (pump discharge)
  - Cooling water

- PWR:
  - ECCS (safety injection)
  - Cooling water

Additionally, due to their requirements for rapid start or frequency of events, the following systems should be provided with keep-full systems:

- BWR:
  - Core spray
  - RHR
  - HPCI
  - RCIC

Keep-full systems are not required for PWR systems because the refueling water storage system acts as an intrinsic keep-full system. The use of a keep-full system for open loop service water systems is impractical due to the continual large line losses. The service water lines are generally very large and very long. Furthermore, much of the line is remote from the main safety areas where the ECCS keep-full system is located, and there is considerable branching with many components served. The use of the ECCS keep-full system for a service water system is impractical. Therefore, the following recommendations are made for filling open loop service water systems. For these systems one of the following should be shown:

a. Voids can be filled within a prescribed time using a manually initiated fill system.

b. Neither column separation nor voiding will occur during standby or following pump shutdown once the line has been filled and vented.

c. The system is designed with a startup mode that slowly fills and vents the discharge lines in such a manner as to prevent water hammer on pump startup. Low-flow bypass valves or slow-opening discharge valves are examples of features that can permit the system to meet this requirement. Analysis and testing would be required to show that slow-fill and system minimum startup time requirements can be achieved.

d. Analysis has determined that the system, including its supports, is designed to maintain function following a postulated water hammer event.

Additionally, venting provisions should be installed at all points where voids could form either through maintenance, operating, draining, out-leakage, gas evolvement, or in-leakage of steam or flashing fluid. The venting system shall be readily operable during all modes of plant operation. Remotely operated valves and valves located for ease of access are suggested types of venting systems. For some systems the use of vacuum breakers may be a desirable feature.

3.5.2 Operator Training

Most of the reported water hammer events involved plant operators and maintenance personnel to a varying degree. They frequently write the plant operating procedures, and ultimately approve them. The operators start the pumps, open the valves and place systems in operation, test, and maintain them.

Over 50% of the events occurred during plant startup and in the twelve months following commercial operation. This indicates there is a learning period during which plant personnel and management become familiar with system operations, change procedures, correct design errors, modify equipment such as vents and drains, and make fewer errors. To be most effective, efforts to reduce water hammer events should start before plant operation and the learning-by-experience period begins.

An investigation of the general causes of operator-involved events indicates the following:

- There is often a lack of awareness among plant operators concerning the water hammer events occurring in a particular system, their causes, and what the results of those events would be. Discussions with various plant operators reveal that they know from experience that water hammers occur, but they have not had specific training as to why or where they happen, what systems are susceptible, or what corrective actions are possible.
- There is a lack of information available to the operators concerning the existing conditions in the systems before the water hammer events occur. A review of the 81 BWR and the 40 PWR water hammer events reported in reference 1 reveals that in only 13 out of the 121 events was applicable instrumentation mentioned as part of the original design to give warning or as part of the repair effort to mitigate further events.
- Equipment malfunctions and maintenance-related failures of components, such as shutoff valves, steam traps, and check valves, are often not fully considered by designers and plant operators with respect to causing water hammer events.

Many water hammer events can be eliminated by design changes that provide the operator with more information (e.g., void detection and improved steam drain pot level indicators), preclude adverse conditions (e.g., vacuum breakers and keep-full systems) and minimize the potential for operator error (e.g., valve interlocks and operability requirements). However, there are many operations, such as line warmup and venting, that require operator knowledge of system conditions. Therefore, plant operators, including personnel responsible for writing maintenance instructions and supervising of maintenance activities, should receive training in the causes and prevention of water hammer.

3.5.3 Turbine Exhaust Line Vacuum Breakers

The turbine exhaust lines of the HPCI and RCIC systems interface with the suppresion pool. Water hammers have been caused by suppression pool water being drawn into these lines due to vacuum formation, as discussed in sections 4.4 and 4.5.

Properly sized vacuum breakers should be installed in both the upstream and downstream sides of the exhaust line stop/check valves for BWR HPCI and RCIC systems. The design should not violate containment isolation requirements.

3.5.4 Turbine Steam Line Drain Pots

The only system in which drain pot operation is considered a significant water hammer concern is the BWR HPCI system (section 4.4). A comparison of the HPCI, RCIC and AFW systems (section 3.4) indicates that the problem may be related to line size.

The adequacy of steam turbine inlet line drain pot sizing should be reviewed for all HPCI systems. If the size is determined to be inadequate, additional or larger drain pots should be installed.

The operability of the steam line drain pot level switches should be verified monthly for HPCI systems. Those systems in which operational verification and maintenance of level switches cannot be performed while the system is in service should be modified to permit such verification and maintenance.

3.5.5 Steam Supply Line Inlet Valves

Water hammer events have been caused by the operation of the HPCI outboard steam line isolation valves. To prevent such events, the technical specifications should prohibit opening the inboard isolation valve unless the outboard isolation valve is fully open, and closing the outboard valve unless the inboard valve is fully closed. These provisions should apply for all conditions except cold shutdown. An interlock may also be provided that will preclude opening the inboard isolation valve unless the outboard isolation valve is fully open. Neither valve should contain a seal-in feature on opening in the manual mode. The inboard valve should be designed for throttling and must be opened slowly to permit gradual line warmup and draining of all liquid. These requirements should apply to the HPCI system.

3.5.6 Anticipated Loads

Certain loads, such as steam hammer due to rapid valve closure or forces caused by safety and relief valve actuation, are to be expected. As an example, turbine stop valves typically close in approximately 0.1 to 0.2 seconds, causing steam hammers.

The forces generated by these loads should be considered in determining the design basis for the piping, its support system, and other components, such as valves. The inclusion of these loads in the design basis for piping is required by NUREG-0737, ASME B&PV Code section III and ANSI B31.1 (references 2, 3, and 4).

3.5.7 Operating and Maintenance Procedures

Many of the water hammer events were reported as having been caused by inadequate operating and maintenance procedures. Additionally, other events might have been avoided had different procedures been available. Because required operator actions are controlled by procedures, adequate operating and maintenance procedures would aid in reducing the frequency of water hammer events.

Certain good practices that aid in preventing water hammer, such as gradual line warmup, controlled valve opening, draining, and venting, are usually covered by procedures. However, discussions with procedure writers and approvers indicate that the potential for water hammer is generally not considered in either procedure writing or review. It was also learned from these discussions that piping drawings, such as isometrics, that show relative piping and component elevations are not used in writing procedures or work instructions.

Operating and maintenance procedures for systems in which safety-related water hammers can occur should be reviewed for their effect on water-hammer occurrence. Additionally, the relative elevations of system lines and components should be considered in writing operating and maintenance procedures. Isometric piping drawings, sufficiently scaled to show relative elevations, are useful in writing procedures and performing maintenance. Such drawings should be available to operating and maintenance personnel as part of the system procedure package.

3.5.8 Line Sloping

A few events have been caused by the inability to properly vent or drain a line due to the location of high and low points. These conditions, however, are detected early, generally during plant startup. To prevent such incidents the design of lines should be reviewed for proper slope and for the location of high and low points in both hot and cold conditions. A similar as-built review of the lines should be performed during startup and any necessary adjustments or modifications to the lines and their supports be made. Line isometric drawings should be updated to reflect as-built conditions.

4.0 BWR SYSTEM EVALUATIONS

This section contains evaluations of water hammer events in BWR plants based on events reported in reference 1. Separate evaluations are provided for each plant system. Each system evaluation is divided into four parts, as described below.

The first part of each system evaluation describes the components and operational features of the system germane to water hammer occurrence and provides a general understanding of the system and its function.

The second part presents an evaluation of the various water hammer events reported in each system and determinations of the probable causes of these events. In addition to the information in reference 1, Licensee Event Reports (LERs), typical system P&IDs, physical drawings, system descriptions and operating instructions, and the design, licensing and operating experience of the authors have been utilized in the evaluations and recommendations. The conclusions reached in this report about the causes and types of some of the water hammer events differ from those presented in reference 1. This is because an event's cause and type cannot always be determined directly or exactly. Therefore, different evaluators may draw different conclusions as to the cause or type of some events.

The safety significance of water hammer in each system is assessed to provide a perspective of the relative importance of water hammer events in the system. The assessment ratings of high, moderate, or low are only relative to water hammer in other systems. They are not ratings of risk to the public or plant personnel. The evaluations considered the frequency and severity of events, along with the system's importance to safety. System safety considerations include system redundancy and the effects of a system failure on safe reactor shutdown and the integrity of reactor coolant and containment boundaries. Also considered in evaluating the safety significance of water hammer were system operability and testing requirements and ability to inspect the system.

Lastly, recommendations specific to each system evaluated are presented. These recommendations are not necessarily considered to be of regulatory concern, but rather, aids in preventing or mitigating water hammers. Generic recommendations that affect all systems, such as those concerned with operator training and procedure writing, are presented in section 3.5. Recommendations deemed significant enough to warrant regulatory review and possible action and their applicable systems are listed in section 6.3.

4.1 Core Spray System

4.1.1 System Description

The core spray system is an ECCS system designed to remove decay heat from the core following a postulated design-basis LOCA. The core spray system, in conjuction with the automatic depressurization system, is capable of cooling the core independently of any other core cooling system.

The core spray system consists of one or two independent loops. Each full capacity loop includes one or two pumps, piping and valves that convey water from the suppression pool to a spray sparger in the reactor vessel above the core, and associated controls and instrumentation. A low-flow bypass line is provided for pump protection. A full-flow test line allows water to be circulated to the suppression pool for system testing during normal plant operation. One testable check valve and one motor-operated valve in each loop isolate the core spray system from the reactor coolant boundary during normal plant operation.

Most core spray systems have a keep-full system and venting provisions to assure that the pump discharge line is always full of water. The keep-full system generally consists of a continuously running low-flow jockey pump that supplies water to the core spray pump discharge line. The venting system generally consists of manually operated valves that vent the discharge line high points.

4.1.2 Water Hammer Evaluation

4.1.2.1 Event Review

Table 4-1 lists the nine core spray water system hammer events reported in reference 1. The cause listed for most (eight of nine) is flow into a voided line. The other event (steam-bubble collapse) could have been initiated by similiar conditions, as will be discussed later. However, it should be noted when using this data for cause evaluation that only five of the nine events were observed. The previous occurrence of a water hammer was reported for the other four events on the basis of observed damage.

4.1.2.2 Water Hammer Causes

The mechanisms which can initiate a water hammer event in a system without proper keep-full operation or venting are described below.

The most common cause of water hammer in core spray systems is line voiding. The relative elevations and valving arrangement of the core spray pump discharge line can cause voiding of lines due to system leakage over a period of time. Draining can occur because the high point of the pump discharge lines is usually 60 to 90 feet above the suppression pool. The pump suction valves must remain open to minimize equipment operation following a core spray actuation signal. Thus, water can drain back to the pool either through a leaking pump discharge check valve or leaking or inadvertently open valves in the bypass test line. The resulting voids may approach vacuum conditions, containing small amounts of gas and water vapor. In this case, there is practically no cushioning effect due to air compression. Thus, large water hammer pulses following pump start can be generated when water is stopped by a closed or partially closed valve.

A properly sized keep-full system, continously operating, will replace the drained water and prevent vacuum conditions from occurring.

Voids containing either air or steam, however, can be introduced into the piping through many means. This is especially true during shutdown or maintenance periods. Voids will not be eliminated by the use of a keep-full system alone, but must be removed by venting. Water hammer can occur when a slug of water is accelerated through a void and suddenly stopped even if the void consists of compressed gas or steam.

Water hammer can also be caused by steam-bubble collapse. Hot water from the reactor can leak past the core spray check valve and injection valve into the core spray pump discharge line, then flash into steam, creating a steam bubble. When the core spray pump starts, the steam bubble collapses, causing a water hammer in the discharge line. Plants having a keep-full system probably will not experience this kind of incident, as the incoming water will condense the steam as soon as it flashes, thereby preventing the formation of a steam bubble. However, if the leak causes the sum of the line pressure and elevation head to become greater than the jockey pump discharge pressure, the pump will not provide water to the line. Systems with high pressure alarms provide the operator with a warning of this situation. Also, valve leakage can cause a steam bubble to occur downstream of an isolation valve. This portion of the piping is generally not serviced by the keep-full system.

4.1.3 Safety Significance

The safety significance of water hammer in core spray systems is high. Nine water hammer events, including several which disabled one train of the system, were reported in reference 1.

The core spray system is part of the ECCS and is connected to the reactor coolant boundary. For most postulated accidents ECCS redundancy is provided by other systems. There are, however, some postulated accidents, which in combination with a single active component failure, would require the use of the core spray system. The connection to the reactor coolant boundary is not significant during testing because the closed isolation valve and the flued head restraint at the containment would prevent the transmission of water hammer forces to the line inside containment.

4.1.4 Recommendations for Prevention or Mitigation

4.1.4.1 Design Phase

a. All core spray systems should be provided with a keep-full system, preferably a continuously operating jockey pump. This is currently standard for most plants.

b. A vent system should be provided that vents all portions of the piping between the pump discharge and the RCP boundary. All venting should be at the line high point. Any portion of piping that is isolated from the system high point by a valve should have a separate vent point.

c. The vent system should either be automatic, remotely operated or designed and located in a manner to maximize the ease of line venting.

d. A monitoring and alarm system should be provided to detect voids.

e. The system should be considered inoperable with respect to technical specification requirements when voids are present in the piping, although it will still be available for emergency use. Voiding should be corrected immediately.

f. A thorough design review should be made to identify all portions of piping in which voids or steam bubbles can form under any operating or standby condition. The operating conditions reviewed should include valve alignments that might occur during maintenance or through operator error.

4.1.4.2 Operational Phase

a. Valves should be leak-checked at every fueling outage. When projected valve leakage is deemed to be large with respect to the keep-full system or void formation, repairs or replacements should be made.

b. Any time the system is to be maintained or aligned in a manner not covered by existing procedures, an evaluation of potential water hammer conditions and venting requirements should be made.

4.2 BWR Residual Heat Removal System

4.2.1 System Description

The combined RHR system is a group of related subsystems that share common components to perform separate functions at different times during normal plant operation, shutdown, and following postulated accidents. The primary system function is to remove heat from the fuel and the nuclear steam supply system (NSSS) during plant shutdown and refueling operations, and following a postulated LOCA. The system consists of two or more heat exchangers, three or more pumps, and required piping, valves, and controls. The components are arranged in separate subsystems, located in the plant's lower elevations, that circulate the coolant water between the fuel, NSSS, suppression pool and the heat exchangers. The most severe system temperature and pressure operating conditions are 150 psia and 350°F, which occur during the plant shutdown cooling and steam condensing modes.

4.2.1.1 Operating Modes

The system has seven principal operating modes, plus a test mode, which are described below.

4.2.1.1.1 Shutdown Cooling

This mode of the RHR system removes decay and sensible heat from the nuclear boiler system after reactor shutdown. When reactor pressure is reduced to approximately 150 psia, an interlock allows the operator to realign the RHR pumps to pump water from one of the reactor recirculation loops through the RHR heat exchanger (Hx) for cooling, and return it to the reactor vessel through the recirculation lines, the feedwater systems or vessel penetrations.

4.2.1.1.2 Reactor Vessel Head Spray

This subsystem is an extension of the RHR shutdown cooling mode. During reactor cooldown, water is pumped from the reactor recirculation system through the RHR heat exchangers and cooled. The water is then sprayed inside the top of the reactor vessel head and condenses the steam that forms there during cooldown.

4.2.1.1.3 Containment Spray

This mode of RHR operation condenses steam and removes heat from the containment to prevent containment overpressure. After operator actuation, suppression pool water is pumped through the RHR heat exchangers by the RHR pumps to either or both of the independent containment spray piping headers, which are installed in an elevated section of the containment.

4.2.1.1.4 Low-Pressure Coolant Injection

This subsystem is part of the ECCS network, and in conjunction with the HPCS, LPCS, and ADS systems, will restore and maintain the reactor vessel water level required for core cooling following a loss-of-coolant accident. When the reactor vessel pressure reaches the low pressure setpoint value, the RHR pumps automatically pump water from the suppression pool directly into the vessel. One pump is a spare. The RHR system is aligned in the LPCI configuration during normal plant power operation.

4.2.1.1.5 Fuel Pool Cooling

This mode of the RHR system supplements the regular fuel pool cooling system when it is necessary to provide additional cooling capability, such as when a complete core is unloaded and stored in the fuel pool. Generally, removable piping spools are installed to connect the two systems. Water from the fuel pool is pumped through the RHR Hx by the RHR pumps, cooled, and then returned to the fuel pool.

4.2.1.1.6 Steam Condensing

This RHR system mode is operator actuated, and is used when the reactor coolant system is isolated from the main condenser. It may be used in conjunction with operation of the RCIC system, to remove decay heat from the reactor. Steam is drawn from the main steam line, reduced in pressure and directed to the shell side of the RHR Hx, where it is condensed by cooling water. The condensate flows to the suction side of the RCIC pump, which returns it to the reactor vessel or to the suppression pool. Noncondensibles are vented to the suppression pool.

4.2.1.1.7 Suppression Pool Cooling

This operator-actuated mode of the RHR system ensures that the suppression pool temperature does not exceed its limit after heat from the reactor has been transferred into the pool. The heat transfer could be from a LOCA, an SRV discharge, or exhaust from the HPCI or RCIC turbines. Suppression pool water is pumped through the RHR Hx by the RHR pumps, where it is cooled and returned to the suppression pool.

4.2.1.1.8 Isolation Condenser

The isolation condenser system, which is a design feature included only in older BWR plants, has been removed from the evaluation of the RHR system. The isolation condenser has different design and operational requirements than the RHR system and is not connected to it. Therefore, the isolation condenser is discussed separately in section 4.3.

4.2.1.2 System Interfaces

The subsystems interface primarily with each other; however, there are system connections to the reactor vessel, the NSSS, the feedwater system, the fuel pool cooling system and to the RCIC system. The RHR steam condensing mode, using the system heat exchangers, interfaces with the RHR pumped water subsystems. Figure 4-1 shows typical steam and water interfaces. The steam-water interface during all power operation modes except steam condensing occurs at valves -13 and -6. During the steam condensing mode the interface is at valve -7.

4.2.2 Water Hammer Evaluation

4.2.2.1 Event Review

Table 4-2 summarizes the 23 BWR residual heat removal system water hammer events reported in reference 1. They have been separated into two classifications: those that occur in subsystems where water is pumped, and those that occur in steam condensing subsystems.

4.2.2.1.1 Pumped Water Subsystems

In the RHR head spray, containment spray, LPCI, fuel-pool cooling and shutdown cooling subsystems, 12 of the 16 events involved flow into a voided line, 2 resulted from steam-bubble collapse, and 2 were from unknown causes. Eleven of the 12 flow-into-voided-line events resulted from poor venting and filling practices.

One of the two steam-bubble collapse events was caused by the collapse of steam that flashed when hot water entered a voided RHR Hx. The other event was caused by steam leakage into the water side of the RHR steam condensing/suppression pool cooling interface. For example, it is possible for a water hammer to occur on RHR pump start (see figure 4-1) when initiating suppression pool cooling. Isolation valve -5 and vent valve -13 can be leaking steam and bubbles could be formed and entrained at the junction of the RHR steam condensing and suppression pool cooling line near valve -7. The line pressurization or introduction of subcooled water into the line due to an RHR pump start could collapse the steam bubbles and result in a water hammer.

4.2.2.1.2 Steam Condensing Subsystems

In the RHR steam condensing subsystem, six of the seven events (14, 15, 16, 17, 20, 25) involved steam-bubble collapse and one event (49) was caused by steam-water entrainment. The six steam-bubble collapse events occurred at the Brunswick plants, and were caused by steam leakage through valves into the RHR Hx inlet piping. The steam-bubble collapse occurred when water was admitted to the line. Five of the six steam-bubble collapse events occurred at the Brunswick 1 plant over a period of fourteen months, and may have been caused by inadequate maintenance or operating procedures. None of the events occurred during the steam condensing mode.

The steam-water entrainment event was caused by condensed steam created during warmup of the HPCI steam supply line, which is connected to the RHR steam condensing piping.

4.2.2.2 Water Hammer Causes

Three causes of recorded water hammer events have been noted in the RHR system, namely, flow into voided line, steam-bubble collapse, and steam-water entrainment.

4.2.2.2.1 Flow Into Voided Line

The most common type of water hammer reported was flow into voided line (12 of 23), which occurred primarily at high point locations in the piping of pumped water systems. Line voiding occurs primarily due to water leakage from the system, combined with inadequate venting and filling. Eleven of the twelve events occurred because of venting or filling problems, or both. The cause of the twelfth event was unknown.

BWR event 41 is an example of a voided line water hammer event. Following an RHR pump start, flow in the fuel pool cooling line entered a pipe section not completely full of water, causing a water hammer. Pipe supports were damaged and a piping section was overstressed. Procedural deficiencies, such as indadequate operating instructions and test procedures, and a design that did not ensure proper venting, were reported as the causes of the event. The operator was unaware of the void when the pump was started.

The installation of keep-full systems in almost all BWR plants has reduced the incidence of flow-into-voided-line events, but some still occur.

4.2.2.2.2 Steam-Bubble Collapse

Steam-bubble collapse is the second most common RHR system water hammer type reported in reference 1 (7 of 23). These events can occur at steam-water interfaces, such as the junction of the RHR steam condensing and shutdown cooling lines, or where a pressure drop could cause hot water to flash, such as in the RHR pump suction lines.

BWR event 33 is an example of the latter case. The plant was near shutdown conditions, and RHR surveillance testing was in progress. The reactor side of the RHR Hx is normally kept in wet layup. Over a two-month period an RHR heat exchanger partially drained due to valve leakage. When the RHR pump suction valves were opened, fluid from the pump suction header flowed to the voided heat exchanger, reducing the header pressure. The pressure reduction caused a vapor bubble to form in the header. When the valves isolating the header from the reactor coolant system were opened, the header was pressurized and the steam bubble collapsed, causing a water hammer. The operator was unaware of the presence of the steam bubble.

When handling water at or close to saturation, any appreciable pressure drop can cause flashing, as happened in event 33. Subsequent pressurization can cause a water hammer unless valves are opened very slowly, or a small bypass around the valve is used.

4.2.2.2.3 Steam-Water Entrainment

The third type of water hammer that occurred in the RHR system was steam-water entrainment. One steam-water entrainment event occurred in the RHR Hx steam condensing inlet line during warmup of the HPCI steam line, which shares portions of piping with the RHR steam line. (BWR event 49). A gradual steam line warmup, slow HPCI valve opening, and inspection of steam line drains could have prevented the event.

4.2.2.2.4 Procedures

Fifteen of the 23 events occurring in the RHR system resulted at least in part from poor procedures, operator error or both. Additional causes (more than one for some events) include lack of venting, incomplete inspection, the lack of a keep-full system, and system leakage. In only two events was inadequate design cited as a cause. All of the above reported causes, except those due to the lack of a keep-full system, involved plant operators and maintenance people. The following factors appear to have contributed to the causes discussed above:

a. Equipment malfunctions and maintenance-related failures of components such as shutoff valves, steam traps, and check valves are not fully considered as part of the causes of water hammer events by designers and plant operators. For example, in 8 of the 23 RHR system events, valve leakage between water and steam systems was a major cause of the event.

b. Venting, filling, and draining of piping were not sufficiently considered in plant procedures prior to subsystem operation, particularly during testing and sytem startup operations. Reference 1 reported inadequate venting and/or filling as a contributing cause for 15 of the 23 RHR system water hammer events.

c. System components have been used in an unintended manner. For example, using gate valves for throttling flow results in valve damage and subsequent leakage. A review of operator practices indicates that this is a common occurrence in pumped water systems, such as the RHR, when throttling valves are not supplied in the proper system locations.

d. Procedures and procedural controls do not fully include consideration of the causes and effects of water hammer. In 15 of the 23 RHR system water hammer events reported in reference 1, procedures and procedural controls were stated as a cause of the event.

4.2.3 Safety Significance

Assessments of the safety significance of water hammer events in each of the RHR subsystems are presented below. Each subsystem has been categorized as having either a high, moderate, or low safety significance.

4.2.3.1 Shutdown Cooling

The safety significance of water hammers in the shutdown cooling mode is high. There were seven system water hammer events, one of which (33) caused damage to a pump suction valve, putting the valve out of service. An alternate suction line was available. The system is safety related. It is operator initiated, and is used for low pressure reactor decay heat removal. The system has mutually redundant trains which could be used in any mode if one of the trains failed to operate or was disabled. In the shutdown cooling mode, the system is connected to the reactor coolant boundary and attached to the primary containment. No events have been severe enough to damage either boundary. The system is inspected during operation and is tested during surveillance testing.

4.2.3.2 Reactor Vessel Head Spray

Water hammer is of low safety significance in the head spray system. There has been only one event reported in the system. The subsystem is nonsafety related. It is operator actuated, and is used only during plant shutdown at low pressures to condense steam inside the RPV head. Subsystem failure would result in a slower RPV cooldown. Inspection can be done only during plant shutdown. The single head spray subsystem event (45) caused a crack in the piping, disabling the subsystem.

4.2.3.3 Containment Spray

The safety significance of water hammer events in containment spray systems is moderate. There were four containment spray system water hammer events (37, 47, 48, 73) reported. One event, 73, disabled one of the two subsystems, leaving one operable. The system is nonsafety-related in some BWR plants, and safety-related in others. It is operator initiated and used as a backup to pressure suppression in a pressure-suppression type of containment. In dry containments it is used to reduce postaccident pressures. If the system is safety-related, there are two redundant containment spray subsystems, either of which can accomplish the system objective. The systems can only be inspected during reactor shutdown, and are tested during surveillance testing.

4.2.3.4 Low Pressure Coolant Injection

The safety significance of water hammer in LPCI systems is low. The only reported event (52) caused pipe and support movement and header damage; however, the system remained operable. The system is safety-related and is automatically actuated as part of the ECCS. There are three separate LPCI subsystems, two of which can accomplish the system objective. Failure of one subsystem due to a water hammer would cause loss of system redundancy but still permit system function. The system is connected to the reactor coolant boundary. The system can be inspected during operation, and is tested during surveillance testing.

4.2.3.5 Fuel Pool Cooling

The safety significance of water hammer in the RHR fuel pool cooling mode is low. The mode is nonsafety-related. It is operator initiated, and is used only during plant shutdown as a backup to the normal plant fuel pool cooling system, whenever extra cooling capacity is needed. If the RHR fuel pool cooling mode fails to operate, other cooling means can be used. Inspection and testing can be done at any time.

There were three subsystem water hammer events (41, 74 44) reported. Following two events radiographic inspection of the piping was performed. In the third event a valve was damaged. In all cases the subsystem remained operable.

4.2.3.6 Steam Condensing

The safety significance of water hammers involving the steam condensing mode is moderate. Although this operational mode is not safety-related, it shares lines with other safety-related portions of the RHR system. All seven water hammers involving the steam condensing mode occurred in safety-related lines. Damage was limited to the pipe support system. Five of the events occurred at one plant, four within the same year, indicating the problem to some degree was plant specific. None of the events occurred while the system was in the steam condensing mode. In all cases the system was returned to service. It is operator initiated, and is designed to be used when the reactor is isolated from the main condenser. The system has two 50% capacity loops. Failure of one-half of the system could cause a slowdown in cooling the NSSS, or require reactor blowdown to the suppression pool. The system is inspected during plant operation and tested during surveillance testing.

4.2.3.7 Suppression Pool Cooling

Water hammer has been of no safety significance in the suppression pool cooling mode, because no water hammer events have been reported in this mode of RHR operation. The system is safety related and is part of the ECCS. It is operator actuated, for long-term cooling of the suppression pool, using the RHR pumps and heat exchangers. There are two separate loops, either of which can achieve the system objective. The system is connected to the primary pressure boundary and to containment penetrations. The system is inspected and tested during plant operation.

4.2.4 Recommendations for Prevention or Mitigation

4.2.4.1 Design Phase

a. All liquid-filled lines should be provided with a keep-full system, preferably a continuously operating jockey pump. This is currently standard for most plants.

b. A vent system should be provided that vents all portions of the liquid-filled piping between the RHR pump discharge and the reactor coolant pressure boundary. All venting should be at the line high point. Any portion of piping that is isolated from the system high point by a valve should have a separate vent point.

c. The vent system should either be automatic, remotely operated or designed and located in a manner to maximize the ease of line venting.

d. A monitoring and alarm system should be provided to detect voids.

e. A thorough design review should be made to identify all portions of piping in which voids or steam bubbles can form under any operating or standby condition. The operating conditions reviewed should include valve alignments that might occur during maintenance or through operator error.

f. Where compatible with the system design, provide slow-closing and -opening flow regulating valves in manually started pumped water systems, instead of gate valves, for throttling service.

4.2.4.2 Operational Phase

a. The system should be considered inoperable when voids are present in the piping. The system will still be available for emergency use. Voiding should be corrected immediately.

b. Establish a leak-reduction maintenance program for valves in the discharge lines of the LPCI, containment spray and head spray subsystems.

c. Special filling and venting procedures should be used following maintenance outages that empty portions of the piping.

d. Any time the system is to be maintained or aligned in a manner not covered by existing procedures, an evaluation of water hammer potential and venting requirements should be made.

4.3 Isolation Condenser System

4.3.1 System Description

The isolation condenser system removes decay heat from the reactor core when the main condenser is not available. The isolation condenser, located outside containment, consists of two tube bundles immersed in a large water tank. Make-up water is available from the condensate storage tank or station firemain storage tanks, and is pumped by either condensate transfer or fire pumps.

The isolation condenser system is included only in the earlier BWR plants, those with dry containment, and a few of the first pressure suppression containment designs. Plants using isolation condensers are no longer being designed or constructed.

When the isolation condenser is in operation, steam flows from the reactor through the tubes of the condenser. After condensing it returns by gravity to the reactor. The isolation condenser is located high in the reactor building to facilitate natural circulation. The valves on the steam inlet lines are normally open to keep the tube bundles at reactor pressure. The isolation condenser is placed in operation by opening the closed condensate return valves to the reactor system. This is done automatically by a high reactor pressure signal or it can be done manually. During operation, the water on the shell side of the condensers will boil and vent to the atmosphere while condensing the steam inside the tube bundles.

Radiation monitors and alarms are provided on the shell vents so that in the event of abnormal radiation levels, the tube side of the heat exchangers can be isolated from the reactor by closing isolation valves. Two isolation valves are provided in the lines connecting the isolation condenser and the reactor. One of the isolation valves is located inside and the other is located outside of the primary containment.

The system interfaces with the nuclear steam supply system through connections to the reactor recirculation piping and the reactor vessel.

4.3.2 Water Hammer Evaluation

4.3.2.1 Event Review

Table 4-3 summarizes the four BWR isolation condenser system water hammer events reported in reference 1. Steam-water entrainment was the only type of water hammer event that occurred in the system. There was some conjecture that steam-bubble collapse may have also taken place in the tank water, caused by the rupture of tubes in the condenser at the same time, in one event (54).

In three events (54, 55, 57) water entered the steam inlet line and impacted the piping and condenser after transient reactor high water level caused water carryover into the steam line to the condenser.

In one event (61), during system start, the lack of venting and improper drainage caused condensed steam to initiate a water hammer.

Of the four water hammer events occurring in the isolation condenser systems, two occurred during plant power operation (54, 61) and two during plant shutdown (55, 57).

Three events (54, 55, and 57) all involved water entering the isolation condenser and occurred at one plant (Millstone 1) over a period of almost four years. No other plants have reported similiar isolation condenser incidents. This indicates that there is a need for Millstone 1 to review their operating procedures with respect to isolation condenser operation and high reactor water levels. It should be noted that except for the damage caused by the tube rupture in event 54, which was attributed to stress corrosion, no damage was noted in an isolation condenser event. The only design-related event (61) occurred during power testing. The design faults were corrected and the system has run for 12 years without accident.

4.3.2.2 Water Hammer Causes

Based on the reported events, the isolation condenser system is susceptible to water hammers caused by transient reactor high water levels during operation. For example, in event 57, reactor normal water level had been maximized in accordance with TMI experience and requirements. Following a scram, when the system was actuated, slugs of water entered the steam inlet piping and caused the event. As a result, instructions directing operators to maximize water level were revised.

Event 54 may have been a hydraulic transient caused by a stress-corrosion-induced condenser tube failure rather than a water hammer. However, a surge in reactor water level caused water to enter the isolation condenser inlet line. Damage was noted in both the condenser and its inlet line.

The isolation condenser system is highly susceptibile to hydraulic transients. The system undergoes a series of mild hydraulic transients each time it is operated. Actuation of the system during high water level in the reactor vessel (above the isolation condenser steam supply connection) will result in a slug of water entering the steam-filled piping, causing momentum, impingement and water hammer forces in the piping and on the condenser tube sheet. These forces can be more severe for an automatic actuation than for a manual one, because the rate of valve opening is not controlled during automatic initiation. If condenser tubes are weakened from stress corrosion, they can rupture, allowing a large steam bubble to form in the tank. The bubble collapses and forms again. This "chugging" can cause large vibrations and noise in the tank.

4.3.3 Safety Significance

The safety significance of water hammer in the isolation condenser has been low, because no piping damage was observed in the four events occurring in the system. In event 54 damage to the isolation condenser was attributed to a corrosion induced condenser tube leak rather than water hammer. Three of the four events occurred at one plant, indicating the events were largely plant specific. If water hammer damage had occurred, the safety significance of water hammer would be high.

The isolation condenser system is often safety-related and essential for safe shutdown. It serves as a replacement heat sink for the main condenser for decay heat removal after reactor scram. The system is connected to the reactor coolant pressure boundary and penetrates the containment.

4.3.4 Recommendations for Prevention or Mitigation

4.3.4.1 Design Phase

No recommendations are made, since isolation condensers are no longer being considered for use.

4.3.4.2 Operational Phase

a. Check cold-to-hot movements of plant components, particularly piping and supports. Adjust supports as needed to reduce vibration and eliminate low spots in drain lines.

b. Procedures should be reviewed with respect to isolation condenser operation and high water levels.

4.4 High-Pressure Coolant Injection System

4.4.1 System Description

The HPCI system consists of a steam-turbine-driven pump along with appropriate piping, valves, and controls, and is part of the ECCS. It is designed to remove heat from the reactor following a postulated loss-of-coolant accident (LOCA) which does not rapidly depressurize the reactor. The HPCI system operates until the reactor pressure is below the pressure at which either the low pressure coolant injection systems (LPCI) or the core spray systems can maintain core cooling. If HPCI is unavailable, the auto depressurization system, in conjunction with core spray or LPCI, can provide the required core cooling.

4.4.1.1 Steam Turbine and Steam Lines

Steam, drawn from upstream of the main steam line isolation valves, drives the HPCI turbine. The two isolation valves in the steam line to the HPCI turbine are normally open to keep piping to the turbine at elevated temperatures and to permit rapid startup of the HPCI system.

To prevent the HPCI system supply line from filling with water, a condensate drain pot is provided upstream of the HPCI turbine stop valve. The drain pot normally routes condensate to the main condenser through an orificed line. The drain pot contains a level switch. A drain pot high level signal opens a bypass line to reduce the drain pot level and actuates an alarm.

Exhaust steam from the HPCI turbine is discharged to the suppression pool. The turbine exhaust line contains check valves to prevent back flow from the suppression pool. A drain pot at the low point in the exhaust line collects condensate which is discharged to a barometric condenser or the suppression pool.

In BWR 5 and 6 plants, the steam-turbine-driven HPCI system has been replaced with an electric-motor-driven high-pressure core spray system. Thus, water hammer incidents associated with steam lines can not occur in these plants.

4.4.1.2 Pump and Pump Discharge Lines

The HPCI system pumps water from either the condensate storage tank (normal alignment) or the suppression pool to a feedwater line in the steam tunnel. A minimum flow bypass to the suppression pool is provided for pump protection. A system test line recirculates the pump discharge to the condensate storage tank during system testing.

The pump discharge line is provided with a vent system consisting of manually operated valves that vent the discharge line high points. Some of the HPCI systems are provided with a keep-full system that generally consists of a continuously running low-flow jockey pump that supplies water to the pump discharge line to compensate for line leakage.

4.4.2 Water Hammer Evaluation

4.4.2.1 Event Review

Table 4-4 presents a summary of HPCI system water hammer events reported in reference 1. The cause listed for most events (12 of 20) is steam-water entrainment. The other events were caused by steam-bubble collapse (four), flow into voided line (three), and unknown (one). When using these data for cause evaluation, it should be noted that water hammer was actually observed in only 10 out of 19 cases. The previous occurrence of water hammer was surmised for the other events on the basis of observed damage.

4.4.2.2 Water Hammer Causes

4.4.2.2.1 HPCI Turbine Steam Supply Line

During normal reactor operation, both the inboard and outboard isolation valves are kept open to maintain steam in the line up to the closed stop valve at the turbine. The drain pot located upstream of the turbine stop valve routes condensed steam to the main condenser through the outlet steam trap. When a high drain pot level occurs, the steam trap bypass valve is automatically opened by a level switch. During HPCI turbine operation, the drain pot valve remains closed.

The drain pot can fail to drain through the outlet steam trap because of plugging of the steam trap orifice. If the drain pot high level switch fails to open the steam trap bypass valve, water will accumulate in the drain pot and steam line. Under these conditions, initiation of steam flow can cause a steam-water entrainment water hammer. During normal HPCI standby conditions, the drain pot will be nearly empty. The level switch and bypass valve are rarely cycled. Such infrequent usage is conducive to the level switch or valve sticking. If the level switch is inoperative, a high water level can occur in the drain pot without any indication to the operator. Events 9, 10, 12, 66, and 67 were caused by level switch malfunction.

There are no provisions for draining the steam line upstream of the outboard isolation valve. Therefore, if an isolation valve is closed, water will accumulate in the line upstream of the valve. Normally, the outboard valve is opened; then the inboard isolation valve is opened slowly for gradual admission of steam. The outboard isolation valve has a seal-in feature that causes the valve to open or close fully; thus the valve cannot be opened gradually. When the outboard valve is opened, with the inboard valve fully open, the steam flow rate builds up rapidly. Entrained liquid in the line flows rapidly through the line and is suddenly stopped at the first obstacle (the turbine stop valve) and large water hammer forces are generated capable of causing significant damage. Events 8, 30, 40, and 50 were caused by isolation valve operation.

4.4.2.2.2 HPCI Turbine Exhaust Line

The turbine steam exhausts into the suppression pool after passing through two check valves, one outside the drywell in a horizontal piping run inside the containment boundary and the other inside the drywell in a vertical piping run. A drain pot at the low point in the exhaust line upstream of the check valves collects condensate which is discharged to a barometric condenser or the suppression pool through a drain pot valve. A level switch automatically opens the drain pot valve on high level.

If the level switch fails to open the drain pot valve on high level, condensed steam will accumulate in the exhaust line. Under such a circumstance, the flow of steam will move this accumulated water, thereby causing a water hammer. This event is less severe than a similar one in the steam supply line, because the exhaust pipe ends in the suppression pool, which has a free surface. Event 24 was caused by a drain switch failure.

After turbine shutdown, rapid steam condensation in the exhaust line can create a vacuum condition, drawing a water slug from the suppression pool into the exhaust line. The water slug, traveling at a high velocity, impacts the check valve disc, resulting in a fast valve closure that can cause a water hammer. The resulting pressure differential can cause a rupture of the turbine exhaust rupture disc. The short operational periods during testing (less than two minutes) are particularly conducive to condensation, because the turbine housing and exhaust line inside walls remain cool and provide a subcooled condensing surface for the stagnant steam remaining in the pipe and turbine after shutdown. Events 7, 11, 60, and 79 were caused by steam condensation.

The vacuum conditions discussed above can cause a slug of water to be trapped between the line check valves. On a subsequent turbine start, the water slug entrained between the two check valves can be propelled past the 90-degree elbow in the exhaust line to impact the suppression pool water interface, causing a water hammer and reaction forces at the piping elbows. Event 2 appears to have been caused by water entrainment.

4.4.2.2.3 HPCI Turbine Gland Seal Condenser Steam Inlet Line

The labyrinth seal steam from either end of the turbine exhausts into a line which drains into the gland seal condenser feed line. The turbine gland seal leak-off drain pot drains both the feed line condensate and the turbine lower casing drains to the suppression pool through a thermostatic trap. If the drain has a high level, an air-operated valve automatically opens and drains the pot to the gland seal condenser.

Failure of the turbine gland seal leak-off drain pot to remove all the water in the line can result in accumulation of liquid in the gland seal condenser inlet line. Subsequent opening of the isolation valve can result in a water hammer. Event 80 was caused by the scenario discussed above.

4.4.2.2.4 Pump Discharge Line

In some plants, the relative elevations and valving arrangement can cause voiding of lines due to normal system leakage over a period of time. The draining problem is primarily due to the difference between the elevation at the pump suction and the pump discharge line. The pump suction valves to the condensate storage tank must remain open to minimize the number of valves to be operated following an actuation signal. Thus, water can drain back from the discharge line to the source through a leaking check valve, leaking or inadvertently open valves in the bypass test line, or by leaking through the minimum flow line. The resulting voids may approach vacuum conditions, containing small amounts of dissolved gas and water vapor. In this case there is practically no cushioning effect due to air compression. Thus, large water hammer pulses following pump start can be generated when a slug of water is accelerated through a void and suddenly stopped. Draining to the source is not a problem in plants where the condensate storage tank level is higher than the high point in the discharge piping.

A properly sized continuously operating keep-full system replaces the drained water and prevents vacuum conditions from occurring. Low-pressure alarms alert the operators of excessive leakage.

Voids containing either air or steam, however, can be introduced into the piping in many ways. This is especially true during shutdown and maintenance periods. Voids will not be entirely eliminated by a keep-full system, but must be removed by periodic venting. Events 13, 19, 27, and 29 were caused by line voiding. The frequency of these incidents in HPCI is considerably less than in the core spray system. This is to be expected, because the elevation difference between the pump suction and the pump discharge line is less than that of the core spray system and the line sizes are smaller. Also, for some plants, the condensate storage tank level is higher than the high point in the discharge piping.

4.4.3 Safety Significance

The safety significance of water hammer in HPCI systems is high. There were 20 events in HPCI systems, three of which (7, 11 and 60) rendered the system inoperative. HPCI is a part of the ECCS and is connected to the reactor coolant pressure boundary. (The steam side is connected upstream of the main steam line isolation valves.) If HPCI is inoperable, the auto depressurization system will provide adequate cooling through depressurization and subsequent use of the core spray and low-pressure coolant injection systems. However, certain postulated accidents in combination with a single component failure require the use of the HPCI.

4.4.4 Recommendations for Prevention or Mitigation

4.4.4.1 Design Phase

A design review should be performed that identifies all portions of piping in which voids or steam bubbles can form or collapse under any operating condition, including valve alignments that might occur during maintenance or through operating error.

4.4.4.1.1 Pump Discharge Line

a. All high pressure coolant injection systems should be provided with a keep-full system, preferably a continuously operating jockey pump. For most plants this feature is already provided.

b. A vent system should be provided that vents all portions of the piping between the pump discharge and isolation valve at the connection with the feedwater piping. All venting should be at the line high points. Any portion of piping that is isolated from the system high point by a valve should have a separate vent point.

c. The vent system should either be automatic, remotely operated, or designed and located for easy access and manual operation.

d. A monitoring and alarm system should be incorporated to detect system leakage and void formation.

e. The system should be considered inoperable when voids are present in the piping. The system will still be available for emergency use. Voiding should be corrected immediately.

4.4.4.1.2 Steam Supply Line

a. The seal-in feature should be removed from the isolation valve opening circuit logic when the valve is in the manual mode.

b. The technical specifications should prohibit opening the inboard isolation valve unless the outboard isolation valve is fully open, and closing the outboard valve when the inboard valve is open. These provisions should apply for all conditions except cold shutdown. Interlocks may also be provided to ensure proper valve opening and closing sequences.

c. Suitable provisions should be made to allow drain pot level switch maintenance during normal plant operation.

d. The adequacy of drain pot sizing should be reviewed. It may be advisable to increase the size of the drain pot or place additional drain pots in parallel.

4.4.4.1.3 Steam Exhaust Line

a. Vacuum breakers should be incorporated both on the upstream and downstream sides of the exhaust line stop/check valves. The design should not violate containment isolation requirements.

b. It is desirable to install a condensing sparger at the end of the exhaust line in the suppression pool to reduce noise and vibration.

4.4.4.1.4 HPCI Turbine Gland Seal Condenser Steam Inlet

The gland seal leak-off drain pot should be sized adequately and should be designed for ease of maintenance during normal plant operation.

4.4.4.2 Operational Phase

a. Procedures should be reviewed for proper warmup of the steam inlet line to provide adequate drainage of steam condensation.

b. Valves should be leak tested at every refueling outage. When projected valve leakage is deemed to be large with respect to the keep-full system capacity, repairs should be made.

c. The drain pot level switch and steam trap bypass valve should be exercised periodically.

d. Any time the system is to be maintained or aligned in a manner not covered by existing procedures, an evaluation of potential water hammer conditions and venting requirements should be performed.

4.5 Reactor Core Isolation Cooling System

4.5.1 System Description

The reactor core isolation cooling system (RCIC) provides makeup water to the reactor vessel, when the reactor vessel is isolated from the main condenser and there is a loss of feedwater flow. The system is used to cool down and depressurize the plant to the point where the shutdown cooling mode of the residual heat removal (RHR) system can be utilized. If for any reason the RCIC system is incapable of supplying sufficient flow for core cooling, the emergency core cooling systems (HPCI, ADS, CS, LPCI) are available to provide the required reactor coolant pressure boundary protection.

The RCIC system consists of a steam-turbine-driven pump unit, associated valves, and piping capable of delivering makeup water to the reactor vessel. The steam is supplied to the turbine from a point upstream of the main steam line isolation valves. The pump is normally aligned to the condensate storage tank but can take suction from the residual heat removal system heat exchangers or the suppression pool. The pump discharges into a feedwater line outside containment on earlier model plants and into the reactor head spray line on later model plants. The pump discharge line is provided with venting provisions consisting of manually operated valves that vent the discharge line high points.

A full-flow test line to the condensate storage tank and a minimum-flow line to the suppression pool are also provided. The minimum flow valve automatically opens on a low flow signal and automatically closes on a high flow signal.

The two isolation valves in the steam line to the RCIC system turbine are normally open to keep piping to the turbine at main steam temperature and to permit rapid startup of the RCIC system. To prevent the steam supply line from filling with water, a condensate drain pot is provided upstream of the turbine stop valve. The drain pot normally routes condensate to the main condenser.

Exhaust steam from the turbine is discharged to the suppression pool through a line containing a check valve. A drain pot at the low point in the exhaust line collects condensate which is discharged to a barometric condenser. In most plants, the exhaust line contains a vacuum breaker to prevent the formation of a vacuum from steam condensation.

4.5.2 Water Hammer Evaluation

4.5.2.1 Event Review

Table 4-5 presents a summary of reactor core isolation cooling system water hammer events reported in reference 1. Two events were observed, a steam-water entrainment water hammer and a pump cavitation incident.

4.5.2.2 Water Hammer Causes

After turbine shutdown, unless the line contains a vacuum breaker, rapid steam condensation in the exhaust line can create a vacuum condition. The vacuum can cause water from the suppression pool to be drawn into the exhaust line. The water slug, traveling at a high velocity, impacts the check valve disc, resulting in fast valve closure, thereby causing water hammer due to sudden stoppage of the slug.

Short operational periods (less than two minutes) are particularly conducive to keeping the turbine housing and exhaust line inside walls cool, thus providing a subcooled surface for condensation of steam remaining in the pipe and turbine after shutdown. Subsequent restart could cause the exhaust steam to expel the water slug and cause large forces when the slug impacts the suppression pool. Event 59 was caused by a water slug in the turbine exhaust lines.

If the pump is started with the test return line valves fully open, the required discharge head is much lower than at the normal operating point. Under such conditions, the pump can cavitate. This could create excessive loading conditions and can cause severe damage to individual pump stages, particularly if their axial movements have not been restrained. Event 77 appears to have been a pump cavitation event and not a water hammer event.

The various water hammer events that have occurred in HPCI systems (section 4.4.2) could conceivably happen in RCIC systems. However, only one RCIC system water hammer incident and one pump cavitation incident have been observed. The smaller line size and length and the recency of introduction of the RCIC system may be the reasons for fewer incidents.

4.5.3 Safety Significance

The safety significance of water hammer in the RCIC system is low. The only water hammer event (59) occurred in the turbine exhaust line, which has no active safety function, but is part of the containment boundary. No damage was indicated for this event. RCIC provides a core cooling function and is a part of the reactor coolant pressure boundary. The steam side is connected upstream of the main steam line isolation valve. If RCIC is inoperable, ECCS systems will provide at least two levels of redundancy.

4.5.4 Recommendations for Prevention or Mitigation

4.5.4.1 Design Phase

4.5.4.1.1 Steam Line

For relieving vacuum conditions in the turbine exhaust line, vacuum breakers should be incorporated on the downstream side of the exhaust line check valve.

4.5.4.1.2 Water Line

a. The reactor core isolation cooling system pump discharge side should be provided with a keep-full system, preferably a continuously operating jockey pump.

b. To simulate normal operational discharge head and flow conditions during testing, a restricting orifice should be installed on the full-flow test return line to the condensate storage tank.

c. Adequate provisions should be made for venting all portions of the piping between the pump discharge and connection with feedwater piping. All venting should be at the line high point. Any portion of piping that is isolated from the system high point by a valve shall have a separate vent point.

4.5.4.2 Operational Phase

a. The RCIC pump should not be started with the test return valve to condensate storage tank fully open. Because a minimum flow line has been provided, there is no danger of overheating if the pump is started against a closed discharge valve.

b. Any time the system is to be maintained or aligned in a manner not covered by existing procedures, an evaluation of potential water hammer conditions and venting requirements should be performed.

4.6 BWR Main Steam System

4.6.1 System Description

The main steam system supplies steam from the reactor vessel to the turbine-generator system. The system consists of main steam piping, safety-relief valves (SRVs), main steam line flow restrictors, turbine stop valves and main steam isolation valves. The steam bypass system bypasses flow to the condenser to control steam pressure during load rejections, reactor heatup, turbine start-up and reactor cooldown.

4.6.2 Water Hammer Evaluation

4.6.2.1 Event Review

Table 4-6 lists the six BWR main steam system events reported in reference 1. Three transient events occurred in the main steam line. Additonally, one event occurred in the SRV discharge line and two events in the steam bypass line. Of these six events, only three (51, 63 and 69) can be considered unanticipated water hammer events. Only events 63 and 65 were unanticipated safety related water hammer events.

Events 51, 63, and 69 occurred in the main steam lines. Events 51 and 69 were caused by turbine stop valve closure, resulting in piping support damage due to inadequate support design. A steam-water entrainment type water hammer probably occurred in event 63, when an isolation valve was suddenly opened during startup valve timing test.

Event 18 occurred in the SRV discharge line. It has been postulated that a sequence of SRV openings resulted in damage to snubbers on a discharge line in the drywell. Analysis indicated that damage to the snubbers should not have occurred if they were functional.

Events 53 and 57 occurred in the steam bypass line. Event 53 occurred in the steam bypass header when the bypass valve was opened. In event 65, steam hammer resulted in damage to snubbers in the main steam bypass line.

4.6.2.2 Water Hammer Causes

Event 63 was considered a steam-water entrainment type water hammer due to sudden opening of the main steam isolation valve, which allowed hot steam to flow into insufficiently warmed downstream line. This water hammer caused a valve operator component to fail. Inadequate valve design contributed to the valve failure.

In event 65, steam hammer was caused by valve cycling due to an out-of-calibration valve control. Control valve instabilities and fluctuations can be minimized by proper inspection and calibration procedures.

In event 53, water hammer was caused by condensate accumulation in the steam bypass header in the main condenser. The end cap of the header failed. Due to its location in the condenser, this water hammer was not safety-related.

Two steam hammer events (events 51 and 69) were caused by sudden valve closure and inflicted damage to pipe support system components because of inadequate design. These events were anticipated steam hammer events. They occurred just prior to or shortly after the start of commercial operation, indicating that inadequate pipe support designs were found early and corrected. Rapid closure of the turbine stop valves and isolation valves is necessary in the main steam lines. Therefore, the design of the pipe support system components for the main steam lines should have included steam hammer dynamic loads resulting from valve closure.

Event 18 was a hydraulic transient in the SRV discharge line with an entrained water slug in the discharge line. The postulated scenario is that, following a reactor scram, reactor pressure increased to the point that an SRV opened. As a result of the SRV opening, the manifold pressure increased causing the water, initially in the adjacent discharge line that shares the same exhaust header, to be pushed upward. The safety relief valve on the line in which the water was pushed upward was then actuated. The expulsion of this water slug from the discharge line caused high loads which resulted in damage to the snubbers. The pipe support system was determined through analysis to be able to withstand the loads, if proper inspection and maintenance procedures were followed. Event 18 was not a true water hammer but a relief valve discharge hydraulic transient with a water slug in the SRV discharge line. It should be noted that BWR SRV discharge lines normally contain a water slug at the exit.

4.6.3 Safety Significance

The safety significance of water hammer in BWR main steam systems is moderate. The reported water hammer events in the main steam system have resulted in damage to the pipe support system components. The main steam lines are safety-related up to and including the outboard isolation valves. The main steam system must be isolated to prevent radiological release during reactor accidents. The attached safety relief valves are a safety-related means of reducing the reactor pressure and removing the reactor heat. No events occurring in the main steam lines have been severe enough to cause piping damage, nor was any damage noted upstream of the main steam isolation valve.

4.6.4 Recommendations for Prevention or Mitigation

4.6.4.1 Design Phase

a. Steam hammer dynamic loads due to valve closure should be included in the design basis of main steam line support systems.

b. Inspection and maintenance procedures for the pipe support system components in the main steam system, including SRV discharge lines, should be developed.

c. Inspection and calibration procedures to detect out-of-calibration valve controls and make necessary corrections should be developed.

d. Valves with components proven to be compatible with the duty cycle and service requirements should be selected.

e. System design and operating procedures should be reviewed for the possibility of water entrainment in steam lines.

f. The steam bypass header design should prevent condensate formation and accumulation.

4.6.4.2 Operational Phase

a. Pipe support system components should be inspected periodically for evidence of wear and damage. Appropriate repairs or replacements should be made when required.

b. Any time the system is to be maintained or aligned in a manner not covered by existing procedures, an evaluation of water hammer potential and venting requirements should be made.

4.7 BWR Feedwater System

4.7.1 System Description

The major components of the feedwater system are feedwater pumps, feedwater regulating valves, and high-pressure heaters. Condensate is pumped from the low pressure heaters by the feedwater pumps into the reactor vessel. The feedwater flow passes through the feedwater regulating valves which automatically control the reactor water level. About 50% of the plants use turbine-driven feed pumps with turbine speed control for feedwater flow control. During startup, the low-flow bypass valves are utilized to control feedwater flow rate. At a flow rate typically about 20% percent of full flow rate, the control is transferred to the feedwater regulating valves and the low-flow bypass valves are closed. Feedwater leaving the valves at a controlled rate enters the final stages of the heating cycle (high-pressure heaters) before entering the reactor vessel.

4.7.2 Water Hammer Evaluation

4.7.2.1 Event Review

The three unanticipated BWR feedwater system water hammer events reported in reference 1 are summarized in table 4-7. In events 71 and 78, water hammer was triggered by feedwater regulating valve instability due to inadequate operator and controller design and possibly incorrect valve trim and/or inadequate inspection and maintenance procedures. Although damage was fairly extensive in both plants, plant safety was not affected. In event 35, water hammer was triggered by the feedwater regulating valve closure due to malfunction of the control system. Damage was also fairly extensive in this event, but the feedwater line was not damaged nor was plant safety affected. It is noted that the plants using turbine speed control for feedwater flow control have not reported water hammers.

In addition to the three water hammer events, seven vibratory, non-water-hammer events were reported in reference 1. Six of the events involved feedwater regulating valve instability and the seventh event involved feedwater regulating valve damage. The combination of water hammer and vibratory events indicates there have been two main problems with the feedwater regulating valves. The most recent feedwater regulating valve event (71) of either type occurred in January 1976.

4.7.2.2 Water Hammer Causes

All of the water hammer and vibratory events occurred after the start of commercial operation. A possible cause of the feedwater regulating valve instability and malfunctions is valve operator and controller deterioration due to excessive cycling. Additionally, the older designs of the valve operator and controller may have been inadequate. Plants had experienced excessive control system hunting and continuous valve cycling for many years.

Early feedwater regulating valves had an anticipatory control system with an internal feedback loop. This control system was characterized by continuous cycling. After 1976, the loop control system was replaced by one that uses a three-element (water level, steam flow, and feedwater flow) controller at high loads and does not contain a feed back loop. Single-element (water level) control is used at low loads, because the three-element controller causes valve cycling at low loads. Cycling occurs because the steam flow signal is not accurate enough at low flow, causing errors in three-element control. The valve actuators were also strengthened to improve their ability to withstand cycling. There have been no feedwater regulating valve incidents reported since the above modifications were made. Additionally, some plants have installed new types of regulatory valves to improve performance.

4.7.3 Safety Significance

The safety significance of water hammer in feedwater systems has been high, but is currently low. There were three water hammer and seven vibration events reported in feedwater systems. However, no events have been reported since January 1976. The reduction of events is probably due to modifications made on the feedwater valve operators and control system discussed in section 4.7.2.2. Loss of feedwater will lead to an emergency shutdown of the reactor. Pressure waves or vibrations have the potential to damage check valves and the connected safety-related RCIC and HPCI lines and to overstress the reactor pressure vessel nozzles on the feedwater line. However, such damage has not occurred. The reported water hammer events in the feedwater system have resulted in fairly extensive damage, although none of the events involved safety of the plants. All of the events were attributed to feedwater valve instability or malfunctions, resulting from valve operator and controller malfunctions.

4.7.4 Recommendations for Prevention or Mitigation

4.7.4.1 Design Phase

a. The controller design should preclude excessive cycling. The use of a three-element control at high loads and single-element control at low loads without a feedback load appears to prevent excessive cycling.

b. The occurrence of spurious signals in a plant is not uncommon. The feedwater control system should be designed to preclude rapid response to such a signal.

c. Select feedwater regulating valves that are properly sized, have balanced trim and are resistant to internal damage.

d. A valve operator should be selected that can meet the feedwater regulating valve performance stability and response requirements. Installation of a hydraulic dampener on the valve stem provides additional valve stability. Maximum valve operation speed under any signal should be limited to five percent/second to avoid severe hydraulic transients.

e. Develop periodic inspection, testing and maintenance procedures to ensure good performance of the regulating valve operator and controller.

4.7.4.2 Operational Phase

a. The feedwater regulating valves should undergo operability checks when placed in service. Valve operator testing should be performed under all conditions to demonstrate that no controller action, including those from spurious signals, can cause water hammer or excessive vibrations.

b. The feedwater regulating valve operator and controller should be periodically inspected and tested to ensure that they are in good working condition. Appropriate repair or replacement should be made when required.

c. Any time the system is to be maintained or aligned in a manner not covered by existing procedures, an evaluation of water hammer potential and venting requirements should be made.

4.8 Reactor Water Cleanup System

4.8.1 System Description

The reactor water cleanup system (RWCU) removes various impurities from the reactor water and provides a means for water removal from the primary system during startup, shutdown or refueling.

Primary water from the reactor recirculation pump suction line and the reactor vessel is pumped through regenerative and nonregenerative heat exchangers where it is cooled, and then through the filter-demineralizer units. The flow then continues through the shell side of the regenerative heat exchanger where it is heated before returning to the reactor through the feedwater line. During times of increasing water volume, excess water is removed from the reactor by blowdown through the cleanup system to either the main condenser or the radwaste system.

4.8.2 Water Hammer Evaluation

Table 4-8 summarizes the only RWCU water hammer event reported in reference 1. It should be noted that water hammer was not actually observed in this case. The previous occurrence of water hammer was surmised on the basis of observed damage.

During standby periods, reduced water temperatures can cause shrinkage and create voids in the system. Subsequent rapid opening of isolation valves can create a flow-into-voided-line water hammer. The resulting forces can damage the piping and adjacent components. Event 38 could have been caused by this scenario.

Event 38 could also have been caused by line vibration induced by improperly installed valves or inadequate pipe supports. The crack in the affected pipe might have resulted from vibration or an existing material defect or both.

4.8.3 Safety Significance

The safety significance of water hammer in RWCU systems is low. Only one event has occurred in RWCU systems and the systems have no safety function. However, the system is connected to reactor coolant pressure boundary and the reported event occurred in this part of the system.

4.8.4 Recommendations for Prevention or Mitigation

4.8.4.1 Design Phase

The isolation valve and its controller should be designed to permit gradual valve opening.

4.8.4.2 Operational Phase

a. While initiating the reactor water cleanup system, the isolation valves should be opened gradually, to avoid a sudden surge of water flow.

b. Valves should be leak-tested periodically. When projected valve leakage is deemed to be large, repairs should be made.

c. When the system is to be maintained or aligned in a manner not covered by existing procedures, an evaluation of potential water hammer conditions and venting requirements should be performed.

4.9 BWR Condenser System

4.9.1 System Description

The main condenser is the steam cycle heat sink. During normal operation, it receives and condenses main turbine exhaust steam, feedwater pump turbine exhaust steam, and turbine bypass steam. The main condenser is also a collection point for other steam cycle miscellaneous flows, drains, and vents. Hotwell level controls provide automatic makeup or rejection of condensate to maintain a normal level in the condenser hot wells. The noncondensable gases contained in the turbine exhaust are collected in the condenser and removed by the condenser air removal system. The condensate pumps take suction from the condenser hot wells and pump water through the trains of heaters to the feedwater system.

4.9.2 Water Hammer Evaluation

Three events were reported in reference 1 in the BWR condenser system. They are summarized in table 4-9. Two out of the three events (75 and 76) occurred in the circulating water line to the condenser. Event 75 was the first of two similar events, caused by inadvertent butterfly valve closure in the circulating water line during maintenance work. As a result, a rubber expansion joint in the condenser water box ruptured, flooding the condensate pump room and damaging the RHR service water pumps and motors and other equipment. Event 76 was the second of the two similar events, again caused by inadvertent valve closure during maintenance work.

Event 70 occurred in the steam bypass line due to bypass valve opening. The water hammer was caused by condensate accumulation in the spargers. The condenser internal spargers and baffle were broken.

All of the three events appear to have been water hammer events, which occurred prior to or shortly after the start of commercial operation. The causes of these events were detected early and corrected.

4.9.3 Safety Significance

The safety significance of water hammer in condenser systems is low, and the system has no safety-related function.

Although the condenser system is not safety related, events 75 and 76 had a safety significance. because a rubber expansion joint rupture in the condenser caused damage to engineered safety equipment due to flooding. Flooding of safety equipment is a pipe rupture rather than a water hammer safety issue. The systematic evaluation program (SEP) and pipe rupture criteria (SRP 3.6.1 and BTP ASB-3-1, references 5, 6, and 7) require analysis of flooding caused by postulated pipe ruptures.

4.9.4 Recommendations for Prevention or Mitigation

4.9.4.1 Design Phase

Note: Recommendation a. is in response to a pipe rupture issue rather than a water hammer issue.

a. Proper locations and design enclosures for engineered safety-system equipment should be selected in the turbine building such that the safety equipment will not be damaged from flooding or other types of accidents. Level switches should be provided to detect flooding. Flooding protection is generally provided by level switches that trip the circulating water pumps should pit flooding occur.

b. Inspection and maintenance procedures should be developed for the circulating water valve hydraulic system to prevent inadvertent valve closure while circulating water is flowing. It is desirable that valve controls and the piping system be designed so that all portions of the piping and condenser can withstand valve closure.

c. Steam bypass spargers should be designed to prevent condensate formation and accumulation.

4.9.4.2 Operational Phase

The condenser internals should be periodically inspected to verify that all components are in good working condition. Appropriate repair or replacement should be made when required.

4.10 BWR Cooling Water Systems

This section evaluates water hammer events occurring in several safety-related BWR cooling water systems. These systems include essential service water, RHR service water and component cooling water. Also included is an event in the cooling tower water system.

4.10.1 System Description

The service water and component cooling water systems provide essential cooling to safety-related equipment and may also provide cooling to nonsafety-related auxiliary components that are required for normal plant operation.

The service water system is an open loop system consisting of two or more pumps taking suction from the ultimate heat sink. The component cooling water system is a closed loop, solid-water system with redundant heat exchangers, cooled by the service water system. A surge tank is connected to the pump suction headers. The pump discharges into a header containing motor-operated valves that allow the pumps be isolated from each other and the redundant trains from each other. Each train provides cooling to one or more of the redundant heat exchangers in the essential safety systems. The nonessential loads are isolated during accident conditions from the essential trains by quick-acting isolation valves. Essential loads needed for shutdown or accident conditions, but not necessary during normal plant operation, have quick-acting valves to bring the equipment online when needed.

4.10.2 Water Hammer Evaluation

4.10.2.1 Event Review

Table 4-10 presents a summary of BWR cooling water systems water hammer events reported in reference 1. No incidents were observed in a component cooling water system. This is to be expected, since each component cooling water system is a closed-loop, solid-water system and has a surge tank on the suction header. The cause listed for five out of nine events is flow into voided line. Two other events were caused by column separation and the causes for two events were not known. When using these data for cause evaluation, it should be noted that water hammer was actually observed in event 46 only. The previous occurrence of water hammer was surmised for the other events on the basis of observed damage.

4.10.2.2 Water Hammer Causes

4.10.2.2.1 Flow Into Voided Line

The following flow-into-voided-line mechanisms may have caused water hammer events in the cooling water systems.

During standby periods, the pressure on the discharge side of a pump can gradually decay, causing voids to form at the high points in the discharge line. On subsequent pump start, the water is accelerated through a void and then is stopped upon impact with the upstream water column causing water hammer. Open-loop service water systems, supplied by an open source, are particularly prone to this type of incident. Events 3, 4, 5 and 6 may have been caused this type of voided-line incident.

Because the manually operated pump discharge valve is normally left open, water in the discharge line could drain through a leaking check valve during a prolonged standby period. On subsequent pump start with the system partially drained, water hammer can result, as may have happened in event 46.

The cooling water line to the RHR service water pump motor cooler is tapped off the pump discharge header. The water flows through the motor cooling-water jacket to a floor drain. Manually operated isolation valves, located before and after the cooling-water jacket, are opened after pump start and closed after pump stop. If the operator forgets to close these valves after pump stop, the discharge side will start draining. On a subsequent pump start, severe water hammer can result. Event 46 may have been caused by this scenario. Similar incidents are not expected to occur in plants where these valves close automatically following pump shut off.

4.10.2.2.2 Water Column Separation

Pressure transients propagated through a liquid system by sudden changes in valve position or pump failure can cause void formation if the pressure drops below the liquid vapor pressure. If the voids form over a considerable fraction of the pipe cross-section, the phenomenon is called column separation. Subsequent pump start or valve opening causes the water slug to accelerate through the void, then stop suddenly upon contact with the downstream water column. The resulting water hammer can cause severe damage. Events 68 and 72 may have been caused by water column separation.

4.10.3 Safety Significance

The safety significance of water hammer in BWR cooling water systems is high. Nine events were reported, several of which damaged system components. Safety-related cooling-water systems provide cooling water to many safety-related systems. Loss of cooling water, therefore, can disable trains of many systems. The safety-related cooling water systems have redundant trains. However, they often share common headers. The systems are tested regularily and can be inspected during plant operation.

4.10.4 Recommendations for Prevention or Mitigation

4.10.4.1 Design Phase

a. A design review should be performed to identify all portions of piping in which voids or column separation can occur under any operating or standby condition, including pump trip and valve alignments that might occur during maintenance or through operating error.

b. A fill system should be incorporated to prevent void formation during standby on the pump discharge side unless it can be shown that either voids cannot form in the system or that the system can be safely started with voids present. Vacuum breakers may be desirable in systems in which startup with voiding is deemed acceptable or to minimize the effects of column separation.

c. Manually operated isolation valves for cooling the RHR service water pump motor should be replaced by automatic valves that open on pump start and close following pump shut-off.

d. A monitoring and alarm system should be incorporated to detect system leakage and void formation.

e. A vent system should be provided that vents all portions of the piping. All venting should be at the line high points. Any portion that is isolated from the system high point by a valve should have a separate vent point.

f. The vent system should either be automatic, remotely operated or designed and located for easy access and manual operation.

4.10.4.2 Operational Phase

a. Valves should be leak-tested periodically. When projected valve leakage is deemed to be large with respect to the keep-full system capacity, repairs should be made.

b. Standby pumps should preferably be started either using a low-flow bypass line or against a closed discharge valve, and then the discharge valve should be gradually opened.

c. Any time the system is to be maintained or aligned in a manner not covered by existing procedures, an evaluation of potential water hammer conditions and venting requirements should be performed.

4.11 BWR Plant Process Steam System

4.11.1 System Description

The plant process steam system supplies steam to various parts of the plant for heating purposes.

4.11.2 Water Hammer Evaluation

One water hammer event (1) occurred in the BWR plant process steam system, as summarized in table 4-11. Event 1 was reported as a steam-bubble-collapse type water hammer in reference 1 and was caused by a marginal design and a procedural deficiency. The design allowed RCS water to backflow into the plant heating system external to the containment, causing a water hammer in the steam supply line from the heating boiler. Operating procedures were either inadequate or not followed in lining up the valves.

4.11.3 Safety Significance

The safety significance of water hammers in the plant process steam system is low. The plant process steam is not safety-related. The probability of damaging the safety-related systems due to a process steam pipe break is very low. The only reported water hammer event in the plant process steam system was plant specific and caused no apparent physical damage.

4.11.4 Recommendations for Prevention or Mitigation

Event 1 occurred about 15 years after the start of commercial operation. This implies that the water hammer was a rare event which was probably caused by operating error. This event is plant-specific, in that the plant process steam system is connected to the RCS in this plant. The water hammer in the steam supply line from the heating boiler caused no apparent physical damage. Furthermore, the plant boiler system is not safety-related. For these reasons, consideration of preventive measures is not necessary for the BWR process steam system.

NOTE 1: No water hammer was actually witnessed. The occurrence of a water hammer was reported based upon observed damage.

Table 4-1 WATER HAMMER EVENTS IN BWR CORE SPRAY SYSTEM

EVENT NO.	PLANT/ DESIGN	COM.OP. DATE	EVENT DATE	OPERATING MODE	WATER HAMMER TYPE	MECHANICAL FUNCTION	INITIAL INDICATION/ DAMAGE	CAUSE AND EVENT BASIS	COMMENTS
31	Dresden-2 GE-3	6/9/70	3/26/71	Testing	Possible flow-into-voided-line	Pump start/ valve opening	Failure of valve to open. Broken switch in the Limitorque operator.	Unknown	Water hammer occurrence was inferred from the damage observed on valve operator switch. Note 1
32	Dresden-2 GE-3	6/9/70	3/29/71	Testing	Flow-into-voided-line	Pump start/ valve opening	Water hammer on pump start. Pipe hangers damaged.	Operation of pump with empty discharge piping.	Update operating procedure so that discharge line is always filled and vented prior to pump start. Install keep full system.
34	Dresden-2 GE-3	6/9/70	7/11/76	95% Power	Possible flow-into-voided-line	Pump start/ valve opening	Outboard injection valve lost open/closed indication and could not be opened electrically. Valve limit switches damaged.	Unknown	See Event 31 Note 1
36	Dresden-3 GE-3	11/16/71	11/27/74	Testing	Possible flow-into-voided-line	Pump start/ valve opening	Normally open valve inadvertently cycled closed and failed to open. Valve limit switches damaged.	Unknown	See Event 31 Note 1
39	Duane Arnold GE-4	2/1/75	4/10/74	Cold Shutdown	Flow-into-voided-line	Pump start/ valve opening	Accidental actuation of core-spray. Anchors were pulled loose from one seismic restraints.	Inadequate administrative controls.	Core spray system should be rendered inoperative when the keep full system is undergoing maintenance.

Table 4-1 (Continued) WATER HAMMER EVENTS IN BWR CORE SPRAY SYSTEM

EVENT NO.	PLANT/ DESIGN	COM.OP. DATE	EVENT DATE	OPERATING MODE	WATER HAMMER TYPE	MECHANICAL FUNCTION	INITIAL INDICATION/ DAMAGE	CAUSE AND EVENT BASIS	COMMENTS
42	Duane Arnold GE-4	2/1/75	2/11/77	85% Power	Flow-into-voided-line	Pump start/ valve opening	Inadvertent initiation of core spray. Loud noises heard. Motor operated clutch housing of spray injection valve fractured.	Procedural deficiency.	Check adequacy of keep full and vent systems against system leakage.
56	Millstone-1 GE-3	3/71	4/17/78	50% Power	Unknown	Valve opening/ closing	Degradation of CS and LPCI piping support systems.	Unknown. Evidence of dynamic loading.	Existence of water hammer condition was inferred from the evidence of large dynamic loading. Note 1
58	Millstone-1 GE-3	3/71	2/20/80	100% Power	Steam-bubble collapse	Pump start	Pipe support damage water hammer during spray pump operability surveillance.	Seat leakage past spray injection valve and check valve.	Review adequacy of keep full system to prevent accumulation of steam bubbles past the injection valve. However, keep full system cannot prevent formation or steam bubble between check valve and injection valve. Some sort of monitoring device needs to be incorporated.
62	Oyster Creek-1 GE-2	12/69	1971	Testing	Flow-into-voided-line	Pump start/ valve opening	Water hammer on pump start. Pipe movement and possible over-stress condition at several points.	Inadequate design and operational procedures. Pump discharging on to empty pipe possibly due to leaky check valve.	Jockey pump system was installed as corrective measure.

NOTE 1: No water hammer was actually witnessed. The occurrence of a water hammer was reported based upon observed damage.

Table 4-2 WATER HAMMER EVENTS IN BWR RESIDUAL HEAT REMOVAL SYSTEM (RHR)

EVENT NO.	PLANT/ DESIGN	COM.OP. DATE	EVENT DATE	OPERATING MODE	WATER HAMMER TYPE	MECHANICAL FUNCTION	INITIAL INDICATION/ DAMAGE	CAUSE AND EVENT BASIS	COMMENTS
45	Hatch-1 GE-4	12/31/75	12/15/74	Shutdown Cooling	Flow into Voided Line	Pump Start Valve Opening	Observed leak in head spray line.	Operator error. Procedural deficiency. Design.	Head spray mode. Improper venting.
47	FitzPatrick GE-4	7/28/75	3/21/75	Cold Shutdown	Flow into Voided Line	Pump Start Valve Opening	Damage found during inspection. Pipe restraints and snubber damaged.	RHR shutdown cooling operation with discharge piping not water filled.	Containment spray mode. Prior to keep full system.
48	FitzPatrick GE-4	7/28/75	5/24/75	Cold Shutdown	Probable Flow into Voided Line	Pump Start Valve Opening	Pipe movement reported. Pipe restraints and snubber damaged.	Unknown.	Containment spray mode. Prior to keep full system. Repeat of 47 Note 1.
73	Quad Cities-1 GE-3	2/18/73	4/3/72	Shutdown	Flow into Voided Line	Pump Start Valve Opening	Water hammer noted. Pipe restraints and hangers damaged.	Occurred during RHR system testing.	Containment spray mode. One system out of service.
37	Dresden-3 GE-3	11/16/71	10/5/79	69% Power	Flow into Voided Line	Valve Opening	Damage found during inspection. Support bolts and spring hanger damage.	Probable water hammer prior to jockey pump installation.	Containment spray mode. Note 1.
52	Millstone-1 GE-3	3/71	6/12/72	Unknown	Flow into Voided Line	Pump Start Valve Opening	Damage found during investigation. Severe pipe movement. Header damaged.	Inadequate operating procedures. Keep full system not in service.	LPCI Mode. Note 1.
41	Duane Arnold GE-4	2/1/75	1/31/77	83% Power. System Test.	Flow into Voided Line	Pump Start Valve Opening	Damage found during inspection. Pipe restraints into hangers damaged. Piping overstressed.	Inadequate operating instructions, test procedures & installation. Improper venting before manual initiation.	Fuel pool cooling mode. Test procedures changed to require venting before test. Note 1.

Table 4-2 (Continued) WATER HAMMER EVENTS IN BWR RESIDUAL HEAT REMOVAL SYSTEM (RHR)

EVENT NO.	PLANT/ DESIGN	COM.OP. DATE	EVENT DATE	OPERATING MODE	WATER HAMMER TYPE	MECHANICAL FUNCTION	INITIAL INDICATION/ DAMAGE	CAUSE AND EVENT BASIS	COMMENTS
74	Quad Cities-1 GE-3	2/18/73	4/4/72	Shutdown	Flow into Voided Line	Pump Start Valve Opening	Noise heard on pump start. Damage found during routine inspection. Valve motor housing failed. Damage pipe restraints and hangers.	Deficient design and procedures. Improper venting upstream of check valves and of tie line to fuel pool cooling system.	Fuel pool cooling mode. Change fill and vent procedures. Use condensate transfer system to replace jockey pump. Note 1.
44	Duane Arnold GE-4	2/1/75	9/27/79	44% Power	Unknown	Valve Opening	Damage found during special inspection. Damaged pipe supports and restraints.	Apparent water hammer.	Fuel pool cooling mode. Note 1.
21	Brunswick-2 GE-4	11/3/75	9/5/75	Shutdown Cooling	Flow into Voided Line	Pump Start Valve Operation	Water hammer heard. Pipe supports and snubber damage, pipe movement.	Inadequate operational test, maintenance, inspection and reporting procedures. Insufficient venting.	Shutdown cooling mode. Revise procedures for venting and keep full system.
22	Brunswick-2 GE-4	11/3/74	9/30/75	Operational Surveillance Test.	Flow into Voided Line	Pump Start	Water hammer heard. Damage same as Event 21.	Inadequate operational test, maintenance, inspection and reporting procedures. Insufficient venting.	Shutdown cooling mode. Add vent points. Revise procedures to minimize valve cycling.
23	Brunswick-2 GE-4	11/3/75	9/30/75	Shutdown Cooling	Flow into Voided Line	Pump Start Valve Operation	Damage noticed during inspection. Damage same as Event 21.	Same as Events 21 and 22.	See Events 21 and 22. Note 1.
33	Dresden-2 GE-3	6/9/70	9/28/71	At Power Surveillance Test	Steam Bubble Collapse	Valve Opening	Water hammer. Neutron flux spikes. Vibration alarm. Valve operator and insulation damage.	Inadequate operating procedures. Valve leakage drained RHR heat exchanger. High water temperature.	Shutdown cooling mode. Valve test to be run only at normal temp.

NOTE 2: Repeat events 14, 15, 16, 17, 20, 25, 26 results from a common cause, steam leakage through steam condensing system valves into RHR piping and Hx. Steam void detection needed.

Table 4-2 (Continued) WATER HAMMER EVENTS IN BWR RESIDUAL HEAT REMOVAL SYSTEM (RHR)

EVENT NO.	PLANT/ DESIGN	COM.OP. DATE	EVENT DATE	OPERATING MODE	WATER HAMMER TYPE	MECHANICAL FUNCTION	INITIAL INDICATION/ DAMAGE	CAUSE AND EVENT BASIS	COMMENTS
64	Peach Bottom-2 GE-4	7/5/74	11/17/75	Shutdown Depressurized	Unknown	Pump Start Valve Opening	Damage found during routine inspection. Broken rigid pipe support.	Unknown	Shutdown cooling mode. Note 1.
26	Brunswick-2 GE-4	11/3/75	4/13/77	72% Power Torus Cooling	Steam Bubble Collapse	Pump Start Valve Opening	Snubber damage.	Administrative controls. Improper installation. Steam leak in vent valve.	RHR torus cooling mode. Venting required prior to manual pump start.
43	Duane Arnold GE-4	2/1/75	12/21/78	Cold Shutdown	Flow into Voided Line	Pump Start Valve Opening	Damage noted during special inspection. Snubber damage.	Defective procedure. System not maintained full during outage.	RHR mode. Need better review of procedures. Note 1.
20	Brunswick-1 GE-4	3/18/77	4/14/81	75% Power	Unknown	Valve Opening	Found snubber damage on steam condensing line to RHR Hx.	Possible water hammer. Lack of venting. Steam leak.	Steam condensing system leak. Increased venting to every 4 hours. Note 2.
14	Brunswick-1 GE-4	3/18/77	3/15/77	96% Power	Steam Bubble Collapse	Pump Start Valve Opening	Snubber damage.	Inadequate operation and inspection procedures. Lack of venting. Steam leak.	Steam condensing system leak. Increase venting of steam condensing line. Note 2.
15	Brunswick-1 GE-4	3/18/77	3/31/77	Torus Cooling	Steam Bubble Collapse	Pump Start	Snubber damage.	Inadequate operation and inspection procedures. Lack of venting. Steam leak.	Steam condensing system leak. Increased venting of RHR steam condensing line. Note 2.
17	Brunswick 1 GE-4	3/18/77	12/20/77	91% Power	Steam Bubble Collapse	Unknown	Broken pipe restraint.	Inadequate detection and administrative procedures. Valves leaking steam into RHR steam inlet piping.	Steam condensing system leak. Pipe supports modified. Note 1. Note 2.

Table 4-2 (Continued) WATER HAMMER EVENTS IN BWR RESIDUAL HEAT REMOVAL SYSTEM (RHR)

EVENT NO.	PLANT/ DESIGN	COM.OP. DATE	EVENT DATE	OPERATING MODE	WATER HAMMER TYPE	MECHANICAL FUNCTION	INITIAL INDICATION/ DAMAGE	CAUSE AND EVENT BASIS	COMMENTS
16	Brunswick-1 GE-4	3/18/77	11/9/77	86% Power. Operability Test.	Unknown	Pump Start	Found broken snubber.	Apparent water hammer. Recurring event in steam condensing line.	Steam condensing system leak. Note 1. Note 2.
25	Brunswick-2 GE-4	11/3/75	10/76	Unknown	Steam Bubble Collapse	Pump Start	Broken shock suppressor	Inadequate administrative procedures. Steam bubble in RHR Hx.	Steam condensing system leak. New procedures needed. Note 2.
49	FitzPatrick GE-4	7/28/75	7/20/75	At Power	Steam Water Entrainment	Valve Opening	Damage found during routine inspection. Restraint damage.	Inadequate operational and inspection procedures Event occurred during RHR Hx/HPCI steam line warmup.	Steam condensing line damage occurred during HPCI system warmup. See Event 50. Note 1.

Table 4-3 WATER HAMMER EVENTS IN THE ISOLATION CONDENSER SYSTEM (BWR)

EVENT NO.	PLANT/ DESIGN	COM.OP. DATE	EVENT DATE	OPERATING MODE	WATER HAMMER TYPE	MECHANICAL FUNCTION	INITIAL INDICATION/ DAMAGE	CAUSE AND EVENT BASIS	COMMENTS
54	Millstone-1 GE-3	3/71	2/12/76	100% Power	Steam Bubble Collapse or Steam Water Entrainment	Generator Trip, Turbine Trip	Ruptured condenser tube caused radiation leak. Reactor high water level caused slugs of water to enter Hx and cause internal damage. Tube rupture was attributed to corrosion rather than water hammer.	Inadequate failure mode alarm and detection system. Procedural deficiencies. Poor operator response. Feed-water valve lockup and MSIV opening caused water level surge over steam inlet.	System is prone to water hammers caused by high reactor water level. System design sensitive to steam bubble collapse and steam water entrainment.
55	Millstone-1 GE-3	3/71	3/11/78	Plant Shut-down. Isolation Condenser in Service	Steam Water Entrainment	Steam Supply Line Valve Opening	Observed movement of steam supply lines.	Procedural Deficiency. A reactor vessel water level increase allowed carry over into steam supply line.	Comments same as Event 54. Snubbers were added to steam line.
57	Millstone-1 GE-3	3/71	12/19/79	Plant Shut-down. Isolation Condenser in Service	Steam Water Entrainment	Steam Supply Line Valve Opening	Observed movement in piping. No damage.	Reactor water level had been maximized based on TMI experience which had allowed water to enter steam supply line.	Comments same as Event 54. Water level instruction revised.
61	Nine Mile Point-1 GE-2	12/69	10/12/69	Power Testing	Steam Water Entrainment	Steam Line Valve Opening	Observed water hammer. Damage unknown.	Inadequate design. No provision for venting or draining piping. No pitch in piping. Too fast heatup when valves opened.	Added drain points. Changed valve and control design. No more water hammer events since commercial operation 12 years ago.

NOTE 1: No water hammer was actually witnessed. The occurrence of a water hammer was reported based upon observed damage.

Table 4-4 WATER HAMMER EVENTS IN BWR HIGH PRESSURE COOLANT INJECTION SYSTEM

EVENT NO.	PLANT/ DESIGN	COM.OP. DATE	EVENT DATE	OPERATING MODE	WATER HAMMER TYPE	MECHANICAL FUNCTION	INITIAL INDICATION/ DAMAGE	CAUSE AND EVENT BASIS	COMMENTS
2	Browns Ferry-1 GE-4	8/1/74	10/72	Pre-op. Testing	Steam Bubble Collapse	Valve Opening	Severe water hammer in HPCI turbine exhaust line. Exhausting steam noise	Inadequate design	Provide vacuum breakers and condensing sparger on turbine exhaust line. Steam exhaust line incident. See Event 79.
7	Browns Ferry-1 GE-4	8/1/74	10/5/73	Power Testing	Possible Steam Bubble Collapse	Valve Opening	Automatic isolation of HPCI system. Turbine discharge inner rupture disc relieved under a vacuum condition.	Procedural deficiency and inadequate design. Vacuum condition created by rapid steam condensation in turbine exhaust line.	Some vacuum relief close to turbine exhaust required. Note 1. Steam exhaust line incident. See Event 2
8	Browns Ferry-1 GE-4	8/1/74	4/4/74	Shutdown	Steam-Water Entrainment	Valve Opening	Water hammer Broken pipe Hangers. Inboard turbine journal bearing pedestal was fractured. Steam supply valve limit switch was broken.	Inadequate design and marginal operating procedures. Rapid opening of outboard isolation valve.	Remove seal-in feature from outboard isolation valve opening logic to allow gradual opening. Provide Technical Specification provisions or interlocks such that inboard valve cannot be opened unless the outboard valve is fully open. Note that gate valves are not suitable for throttling. Steam supply line incident.
9	Browns Ferry-1 GE-4	8/1/74	1/27/80	Shutdown	Steam-Water Entrainment	Valve Opening	Crack in HPCI turbine coupling bearing support pedestal.	Possibly caused by an observed water hammer in the steam supply line while warming the HPCI system from an out-of service condition.	Note 1 Steam supply line incident.

Table 4-4 (Continued) WATER HAMMER EVENTS IN BWR HIGH PRESSURE COOLANT INJECTION SYSTEM

EVENT NO.	PLANT/ DESIGN	COM.OP. DATE	EVENT DATE	OPERATING MODE	WATER HAMMER TYPE	MECHANICAL FUNCTION	INITIAL INDICATION/ DAMAGE	CAUSE AND EVENT BASIS	COMMENTS
10	Browns Ferry-1 GE-4	8/1/74	1/29/80	Shutdown	Steam-Water Entrainment	Valve Opening	Broken instrument sensing line hangers.	Possibly caused by an observed water hammer in the steam supply line while warming the HPCI system from an out-of-service condition.	Events 9 and 10 might have been caused by the same incident but the consequences were observed at different times. Note 1. Steam supply line incident.
11	Browns Ferry-2 GE-4	3/1/75	8/11/74	5% Power	Possible Steam-Water Entrainment	Valve Opening	Automatic isolation of HPCI system. Turbine exhaust rupture disc relieved.	Possible water in turbine exhaust line when steam was admitted. Exhaust drain line solenoid burned up due to wiring error on installation. Defective switching element inside level switch deactivated drain valve.	Water hammer caused by equipment failure due to maintenance error. Note 1. Steam exhaust line incident.
12	Browns Ferry-2 GE-4	3/1/75	2/16/80	Shutdown	Possible Steam-Water Entrainment	Valve Opening	Cracks in turbine coupling bearing support pedestal.	Design and operational deficiency possibly water hammer during HPCI system warm up from out-of-service condition.	Note 1 Steam supply line incident.
13	Browns Ferry-3 GE-4	3/1/77	1/26/77	100% Power	Unknown	Pump Start	Restraints on the pump discharge line and loose bolts and broken anchors.	Unknown	Note 1 Pump discharge side incident.

Table 4-4 (Continued) WATER HAMMER EVENTS IN BWR HIGH PRESSURE COOLANT INJECTION SYSTEM

EVENT NO.	PLANT/ DESIGN	COM.OP. DATE	EVENT DATE	OPERATING MODE	WATER HAMMER TYPE	MECHANICAL FUNCTION	INITIAL INDICATION/ DAMAGE	CAUSE AND EVENT BASIS	COMMENTS
19	Brunswick-1 GE-4	3/18/77	3/28/81	90% Power	Possible Flow-Into-Voided-Line	Valve Opening	Damaged piping supports	Design and operational deficiency. Inadequacy of keep full system relative to system leakage.	Note 1. Keep full system by itself will not eliminate water hammer problem. Check keep fill system capacity against possible system leakage. Install monitoring system to detect system leakage and void formation. Pump discharge side incident.
24	Brunswick-2 GE-4	11/3/75	9/76	Shutdown	Steam-Water Entrainment	Valve Opening	Water Hammer Excessive turbine exhaust line movement resulting in shock suppressor and hanger damage at several locations.	Exhaust piping was not drained because of a malfunction of a drain level switch and failure of a solenoid valve.	Modify system design to allow maintenance of level switch during normal plant operation. Steam exhaust line incident.
27	Brunswick-2 GE-4	11/3/75	3/24/78	Shutdown	Possible Flow-Into-Voided-Line	Valve Opening	Snubber with broken shaft on HPCI discharge line.	Probably due to sticky check valve of keep full system.	Note 1. Pump discharge side incident.
29	Brunswick-2 GE-4	11/3/75	3/28/81	90% Power	Possible Flow-Into-Voided-Line	Valve Opening	Damaged piping supports	Design and operational deficiency. Inadequacy of keep full system relative to system leakage.	Note 1. Pump discharge side incident.

Table 4-4 (Continued) WATER HAMMER EVENTS IN BWR HIGH PRESSURE COOLANT INJECTION SYSTEM

EVENT NO.	PLANT/ DESIGN	COM.OP. DATE	EVENT DATE	OPERATING MODE	WATER HAMMER TYPE	MECHANICAL FUNCTION	INITIAL INDICATION/ DAMAGE	CAUSE AND EVENT BASIS	COMMENTS
30	Dresden-2 GE-3	6/9/70	5/29/70	Power Testing	Steam-Water Entrainment	Valve Opening	Water hammer damage to piping.	Design and procedural deficiency.	Comment for Event 8 applies. Steam supply line incident.
40	Duane Arnold GE-4	2/1/75	6/11/74	30% Power	Steam-Water Entrainment	Valve Opening	Normally open outboard steam supply isolation valve was indicating closed; damage to pipe insulation, pipe hanger, seismic snubbers, pressure indicator and steam line drain pot indicator.	Design and procedural deficiency; operator error; movement and impact of water slug from steam condensation occurred in the steam supply line when the outboard isolation valve was opened while the inboard isolation valve was full open.	Comment for Event 8 applies. Steam supply line incident.
60	Monticello GE-3	6/30/71	7/17/72	Surveillance Testing	Possible Steam Bubble Collapse	Turbine Exhaust Stop Check Valve Operation	Turbine trip. Failed check valve pin caused line blockage; steam issuing from relieved exhaust line rupture discs impinged on adjacent temperature switches rendering them inoperable.	Inadequate component and subsystem design.	Equipment failure leading to water hammer. Note 1. Steam exhaust line incident.
66	Peach Bottom-3 GE-4	12/23/74	2/14/75	100% Power	Steam-Water Entrainment	Valve Opening (Steam-Line)	Movement of steam supply line.	Inoperative component and administrative deficiency. Failure of steam trap to drain properly and drain pot level switch to trip on high level.	Equipment failure leading to water hammer. Steam supply line incident.

Table 4-4 (Continued) WATER HAMMER EVENTS IN BWR HIGH PRESSURE COOLANT INJECTION SYSTEM

EVENT NO.	PLANT/ DESIGN	COM.OP. DATE	EVENT DATE	OPERATING MODE	WATER HAMMER TYPE	MECHANICAL FUNCTION	INITIAL INDICATION/ DAMAGE	CAUSE AND EVENT BASIS	COMMENTS
67	Peach Bottom-3 GE-4	12/23/74	12/2/75	57% Power	Steam-Water Entrainment	Valve Opening (Steam Line)	Movement of steam supply line.	Inoperative component and administrative deficiency. Failure of steam trap to drain properly and failure of the drain pot level switch to trip on high level.	Identical to Event 66 Steam supply line incident.
79	Vermont Yankee GE-4	11/30/72	1971	Pre-op. Testing	Steam Bubble Collapse	Exhaust Line Check Valve Closure	Water hammer	Design and procedural deficiency. Fast turbine exhaust line check valve closure due to vacuum condition.	Steam exhaust line incident. See Event 2
80	Vermont Yankee GE-4	11/30/72	6/76	88% Power	Possible Steam-Water Entrainment	Valve Opening/ Pump Start	Leakage	Operator error and design deficiency. Operator accidently drained reference leg of an RV level control instrument and gland seal head gasket failed on system start.	Note 1. Gland seal condenser steam line incident.
50	FitzPatrick GE-4	7/28/75	9/7/75	Startup	Steam-Water Entrainment	Valve Opening	Damaged several pipe restraints on steam line to RHR heat exchanger.	Insufficient drainage of condensed steam during HPCI line warmup.	Note 1 Provide adequate drainage of steam supply line. Steam supply line incident.

Table 4-5 WATER HAMMER EVENTS IN BWR REACTOR CORE ISOLATION COOLING SYSTEM

EVENT NO.	PLANT/ DESIGN	COM.OP. DATE	EVENT DATE	OPERATING MODE	WATER HAMMER TYPE	MECHANICAL FUNCTION	INITIAL INDICATION/ DAMAGE	CAUSE AND EVENT BASIS	COMMENTS
59	Monticello GE-3	6/30/71	1971	Unavailable	Steam Water Entrainment	Unavailable	Water Hammer	Inadequate design	Steam exhaust line incident. Provide vacuum breakers on turbine exhaust line.
77	Quad Cities-1 GE-3	2/18/73	10/29/76	94% Power	Pump Cavitation (Not a water hammer problem)	Valve Opening	Pump failed to develop required head and flow Two of five pump stages were severely damaged.	Faulty operational procedure and mechanical design. Pump startup with test return valve to condensate storage tank open.	Pump cavitation incident. Revise pump start procedure

NOTE 1: No water hammer was actually witnessed. The occurrence of a water hammer was reported based upon observed damage.

Table 4-6 WATER HAMMER EVENTS IN BWR MAIN STEAM SYSTEM

EVENT NO.	PLANT/ DESIGN	COM. OP. DATE	EVENT DATE	OPERATING MODE	WATER HAMMER TYPE	MECHANICAL FUNCTION	INITIAL INDICATION/ DAMAGE	CAUSE AND EVENT BASIS	COMMENTS
18	Brunswick-1 GE-4	3/18/77	12/12/79	0% Power	SRV discharge transient	SRV lifting	Discovered damaged snubbers. Variety of damage to ten different snubbers on S/RV discharge line.	Reactor scrammed and relief valves lifted. Analysis indicated that a water slug could cause the damage if selected snubbers were non-functional.	Note 1. Frequent inspection of snubbers required to assure operability.
51	Millstone-1 GE-3	3/71	12/9/70	Startup (50% load turbine trip test)	Steam hammer	Turbine stop valve closure, turbine bypass valve instability	Damage to MS piping. Escessive movement of main steam lines and bypass lines. Fixed pipe support common to all four main steam lines, between outboard isolation and turbine stop valves, stressed beyond yield. Line movement damaged other support steel and instrument connections.	Inadequate piping support design (failure to consider dynamic forces generated by rapid closure of stop valves). During a planned turbine trip the rapid closure of the MS stop valves caused a transient. A contributing cause was malfunction of bypass valve actuator components.	Note 1. Piping support design should include loading due to dynamic force generated by rapid valve closure. Ensure that valve component selection is compatible with duty cycle and service requirement.
63	Oyster Creek-1 GE-2	12/69	11/16/71	Startup (valve timing test)	Steam hammer	Sudden MSIV opening	Incomplete MSIV closure. Valve operator cast iron speed cushion crushed with pieces preventing valve closure.	Inadequate valve design (component/service condition incompatibility) and/or sudden valve opening with large pressure differential (800 psi) existing across valve disc.	Note 1. Ensure that valve component selection is compatible with duty cycle and service requirement. Check operating procedure for warm up during startup.
53	Millstone-1 GE-3	3/71	1972	Unavailable	Steam water entrainment	Steam bypass valve opening	Structural failure of steam bypass header at main condenser. End cap of steam bypass header failed.	Inadequate design of steam bypass header (hole sizes and numbers of holes in header insufficient). Condensate formation and accumulation in steam bypass header.	Note 1. Check design for possibility of condensate formation and accumulation in steam bypass header.

NOTE 1: No water hammer was actually witnessed. The occurrence of a water hammer was reported based upon observed damage.

Table 4-6 (Continued) WATER HAMMER EVENTS IN BWR MAIN STEAM SYSTEM

EVENT NO.	PLANT/ DESIGN	COM. OP. DATE	EVENT DATE	OPERATING MODE	WATER HAMMER TYPE	MECHANICAL FUNCTION	INITIAL INDICATION/ DAMAGE	CAUSE AND EVENT BASIS	COMMENTS
65	Peach Bottom-3 GE-4	12/23/74	10/15/74	Power escalation testing	Steam hammer	Bypass valves cycling	Damage to piping system observed. Snubbers on piping between bypass valves and main condenser damaged.	Valve maintenance deficiency (improper EHC calibration). Out-of-calibration acceleration amplifiers in the electro hydraulic controls system caused valve cycling.	Note 1. Develop inspection and calibration procedures to detect out-of-calibration valve control and make necessary corrections as required.
69	Pilgrim-1 GE-3	12/72	7/24/72	Power escalation testing	Steam hammer	Startup test program involving repeated closure of turbine stop valve and control valve	Damage to piping system observed. Pipe hanger torn from support on one main steam line. Bent hangers on three other main steam lines downstream of MSIV near second elbow.	Inadequate piping support design (failure to consider cumulative concurrent loading). The additional dynamic loading induced by valve closure acted concurrently with existing loads to overstress a pipe support.	Note 1. Piping support design should include loading due to dynamic force generated by rapid valve closure.

NOTE 1: No water hammer was actually witnessed. The occurrence of a water hammer was reported based upon observed damage.

Table 4-7 WATER HAMMER EVENTS IN BWR FEEDWATER SYSTEM

EVENT NO.	PLANT/ DESIGN	COM. OP. DATE	EVENT DATE	OPERATING MODE	WATER HAMMER TYPE	MECHANICAL FUNCTION	INITIAL INDICATION/ DAMAGE	CAUSE AND EVENT BASIS	COMMENTS
71	Pilgrim-1 GE-3	12/72	1/6/76	Power increase	Unknown (vibration), possible column separation	FW regulating valve instability (valve cycling)	FW system vibrations. Yoke of startup regulating valve fractured resulting in complete ejection of valve stem. Valve body cracked. Pipe hanger bent on FW line.	Inadequate valve operator design, component/service condition incompatible. Cycling of FW valve due to faulty pneumatic valve operator induced flow vibrations.	FW regulating valve instability caused water hammer. Select valve operator and controller that can meet the control valve performance and response requirements.
35	Dresden-3 GE-3	11/16/71	6/23/74	At power in run mode	Unknown	Regulating valve closure	FW regulating valve lock up; service air compressor, RWCU pump, and FW heater tripped; FW and reactor level decreased. FW low flow regulating valve opened and rotated with all air lines and electrical feeds broken. Damage to piping support system components in FW lines.	Specific cause not identified. FW valve vibration and inadvertent closure possibly related control system malfunction.	Note 1. See Event 71
78	Quad Cities-2 GE-3	2/18/73	8/31/75	Decreasing load for shutdown	Unknown (vibration)	Regulating valve instability	FW vibration alarm, turbine trip due to reactor high water level, reactor scram, FW system leak. FW low flow drain lines and high pressure heater bypass line broken.	Inadequate valve actuator design. FW system vibration possibly caused by flow/response condition of FW valve actuator piston.	See Event 71

NOTE 1: No water hammer was actually witnessed. The occurrence of a water hammer was reported based upon observed damage.

Table 4-8 WATER HAMMER EVENTS IN BWR REACTOR WATER CLEANUP SYSTEM

EVENT NO.	PLANT/ DESIGN	COM.OP. DATE	EVENT DATE	OPERATING MODE	WATER HAMMER TYPE	MECHANICAL FUNCTION	INITIAL INDICATION/ DAMAGE	CAUSE AND EVENT BASIS	COMMENTS
38	Dresden-3 GE-3	11/16/71	4/2/80	Refueling	Unknown	Valve Opening/ Closing	Fully retracted mechanical snubber. Crack in affected pipe between first isolation valve and containment penetration.	Possible operation or material deficiency.	Note 1 After nine years of operation only one event was observed. Crack in the affected pipe did not cause any leak. Ultrasonic test detected the crack. Radiographic test did not confirm this indication. This suggests that the crack may be parallel to the surface.

NOTE 1: No water hammer was actually witnessed. The occurrence of a water hammer was reported based upon observed damage.

NOTE 2: The condenser system is non-safety related. However, nuclear safety considerations are involved when engineered safety system equipment is damaged due to flooding such as in Events 75 and 76.

Table 4-9 WATER HAMMER EVENTS IN BWR CONDENSER SYSTEM

EVENT NO.	PLANT/ DESIGN	COM. OP. DATE	EVENT DATE	OPERATING MODE	WATER HAMMER TYPE	MECHANICAL FUNCTION	INITIAL INDICATION/ DAMAGE	CAUSE AND EVENT BASIS	COMMENTS
75	Quad Cities-1 GE-3	2/18/73	6/9/72	Hot shutdown (maintenance outage)	Probable column separation	Circulating water butterfly valve closure	Sudden, inadvertent valve closure. While venting the recirculating valve hydraulic system, a rubber expansion joint in the condenser water box ruptured and recirculation water flooded the condensate pump room. Water immersion damaged RHR service water pumps and motors and other equipment.	Inadequate maintenance or repair practices. While performing condenser modifications, a butterfly valve slammed closed while condenser circulating water pumps were in operation. This event occurred while venting the valve hudraulic oil system.	Notes 1 and 2. Develop maintenance procedure for circulating water valve hydraulic system to prevent inadvertent valve closure, while circulating water is flowing. Select location and design enclosure of engineered safety equipment such that the safety equipment will not be damaged from flooding or other types of accident.
76	Quad Cities-1 GE-3	2/18/73	1973	Unavailable	Column separation	Circulating water butterfly valve closure	Unavailable. Rupture of rubber expansion joint in line. Damaged engineered safety-system equipment due to flooding.	During maintenance work, malfunction caused a butterfly valve to slam shut resulting in water hammer.	Notes 1 and 2 See Event 75
70	Pilgrim-1 GE-3	12/72	1972	Unavailable	Probable steam-water entrainment	Steam bypass valve opening	Broken spargers and baffle damage in condenser. Condenser internal spargers were broken.	Inadequate design of sparger. Probably condensate formation and accumulation in sparger.	Note 1. Check design for possibility of condensate formation and accumulation in sparger.

NOTE 1: No water hammer was actually witnessed. The occurrence of a water hammer was reported based upon observed damage.

Tabel 4-10 WATER HAMMER EVENTS IN BWR COOLING WATER SYSTEM

EVENT NO.	PLANT/ DESIGN	COM.OP. DATE	EVENT DATE	OPERATING MODE	WATER HAMMER TYPE	MECHANICAL FUNCTION	INITIAL INDICATION/ DAMAGE	CAUSE AND EVENT BASIS	COMMENTS
3	Browns Ferry-1 GE-4	8/1/74	5/6/73	Unavailable	Possible flow-into-voided-line. Non-essential water system.	Pump start	Failure of orifice gasket.	Design and procedural deficiencies. Voids form due to line leakage and dissolved gases collect at high points during standby periods. On pump start the water compresses these gases or forces them into solution such that the water interfaces come in contact causing damaging water hammer.	Note 1 Improve surveillance or add void alarm system.
4	Browns Ferry-1 GE-4	8/1/74	5/10/73	Unavailable	Possible flow-into-voided-line. RHR service water system.	Pump start	Failure of pipe coupling.	See Event 3	Note 1 See Event 3
5	Browns Ferry-1 GE-4	8/1/74	5/23/73	Unavailable	Possible flow-into-voided-line. RHR service water system.	Pump start	Failure of pipe coupling.	See Event 3	Note 1 See Event 3
6	Browns Ferry-1 GE-4	8/1/74	6/7/73	Unavailable	Possible flow-into-voided-line. RHR service water system.	Pump start	Failure of pipe coupling.	See Event 3	Note 1 See Event 3
28	Brunswick-2 GE-4	11/3/75	4/12/80	Zero Power	Unknown RHR service water system.	Valve Opening/ Closing	Partially buckled HX rib plate.	Procedural deficiency.	Note 1 Operating procedures should be revised to require venting.

Table 4-10 (Continued) WATER HAMMER EVENTS IN BWR COOLING WATER SYSTEM

EVENT NO.	PLANT/ DESIGN	COM.OP. DATE	EVENT DATE	OPERATING MODE	WATER HAMMER TYPE	MECHANICAL FUNCTION	INITIAL INDICATION/ DAMAGE	CAUSE AND EVENT BASIS	COMMENTS
46	FitzPatrick GE-4	7/28/75	4/10/74	Functional Testing	Flow-into-voided-line. RHR service water system.	Pump start/ valve opening.	Water hammer; piping movement. The bottom of the pump discharge basket strainer was blown off and grouting for strainer support was chipped. Buckled piping at seismic trunion locations. Bent seismic trunions, a pipe support with a failed turnbuckle, and a pipe support with failed anchors near the pump.	Procedural deficiency. The pump discharge valve and motor cooler isolation valves were not closed and remained open over night causing the system to drain.	The pump discharge valve and motor cooler isolation valves should normally be kept closed and be gradually opened on pump startup.
68	Peach Bottom-2 and 3 GE-4	7/5/74 12/73/74	5/76	Refueling Shutdown from 70% power.	Possible column separation. Cooling water system.	Pump start/ valve opening.	Water gushing from lift pump house door. Bolts holding suction bell housing to pump casing failed. Discharge piping cracked and base plate shifted.	Unknown; possible design/ procedural deficiency. Observed damage is indicative of water hammer on pump start due to column separation/voided line flow.	Not safety-related.
72	Pilgrim-1 GE-3	12/72	2/3/77	5% power	Possible column separation. Essential service water system.	Pump start/ valve opening.	Salt water service pump failed to start. The top column pipe had a 360 degree fracture just below its top flange allowing the pipe to drop into and jam the pump impeller.	Unknown; possible design/ procedural deficiency. Observed damage is indicative of column separation in discharge line.	Note 1 See Event 3
81	Vermont Yankee GE-4	11/30/72	12/4/79	99% power	Unknown	Condenser storage tank, valve opening/ closing	Damaged hanger found during support inspection. Damage to pipe hanger.	Not conclusive, but attributed to water hammer developed during full flow surveillance testing of associated safety system.	Note 1 Possible deficiency in pipe hanger design.

NOTE 1: No water hammer was actually witnessed. The occurrence of a water hammer was reported based upon observed damage.

Table 4-11 WATER HAMMER EVENTS IN BWR PLANT PROCESS STEAM SYSTEM

EVENT NO.	PLANT/ DESIGN	COM. OP. DATE	EVENT DATE	OPERATING MODE	WATER HAMMER TYPE	MECHANICAL FUNCTION	INITIAL INDICATION/ DAMAGE	CAUSE AND EVENT BASIS	COMMENTS
1	Big Rock Point GE-2	3/29/63	10/31/77	Unavailable	Steam bubble collapse	Plant heating boiler, valve opening.	Water hammer occurrence. No apparent physical damage. Event resulted in a minor, uncontrolled release of radioactive water to discharge canal.	Marginal design concepts and procedureal deficiency. During manual valving operations RCS water back-flowed into the plant heating system external to the containment causing a water hammer in the steam supply line from the heating boiler. Operating procedures were not followed in the valve line up.	Plant specific Event.

5.0 PWR SYSTEM EVALUATIONS

This section contains evaluations of water hammer events in PWR plants based on events reported in reference 1. Separate evaluations are provided for each system. Each system evaluation is divided into four parts, as described below.

The first part of each system evaluation describes the components and operational features of the system germane to water hammer occurrence and provides a general understanding of the system and its function.

The second part presents an evaluation of the various water hammer events reported in each system and determinations of the probable causes of these events. In addition to the information contained in reference 1, Licensee Event Reports (LERs), typical P&IDs, physical drawings, system descriptions, operating instructions, and the design, licensing and operating experience of the authors have been utilized in the evaluations and recommendations. The conclusions reached in this report about the causes and types of water hammers differ from those presented in reference 1. This is because an event's cause and type cannot always be determined directly or exactly. Therefore, different evaluators may draw different conclusions as to the cause or type of some events.

The safety significance of water hammer in each system is assessed to provide a perspective of the relative importance of water hammer in the system. The assessment ratings of high, moderate, or low are only relative to water hammers in other systems. They are not ratings of risk to the public or plant personnel. The evaluations considered the frequency and severity of events, along with the system's importance to safety. System safety considerations include system redundancy and the effects of a system failure on safe reactor shutdown and the integrity of reactor coolant and containment boundaries. Also considered in evaluating the safety significance of water hammer were system operability and testing requirements and the ability to inspect the system.

Lastly, recommendations specific to each system evaluated are presented. The recommendations are not necessarily considered to be regulatory concerns, but rather, aids in preventing or mitigating water hammers. Generic recommendations that affect all systems, such as those concerned with operator training or procedure writing, are presented in section 3.5. Recommendations deemed significant enough to warrant regulatory review and possible action and their applicable systems are listed in section 6.3.

5.1 PWR Feedwater System

5.1.1 System Description

The feedwater system pumps condensate from the low-pressure heaters to spargers in the steam generators. The feedwater system consists of feedwater pumps, feedwater heaters, feedwater control and isolation valves, associated piping and instrumentation. The feedwater valves control feedwater flow rate based on input signals of main steam flow, feedwater flow and steam generator level. Feedwater bypass valves are used for flow control under low-flow conditions. The feedwater pumps are provided with low-flow bypass lines and trip logic for low net positive suction head protection.

Auxiliary feedwater (AFW) and chemical injection lines are connected to the main feedwater lines. The AFW lines are part of the AFW system, which is a safety-related system designed to remove heat from the reactor coolant system by use of the steam generators.

5.1.2 Water Hammer Evaluation

5.1.2.1 Event Review

Table 5-1 presents a summary of the nonsteam generator PWR feedwater system water hammer events reported in reference 1. Steam generator water hammers were excluded from the scope of this document, because they are reviewed elsewhere (references 8 and 9). The feedwater system contributed to 13 of the 40 PWR nonsteam-generator water hammer events reported in reference 1. Only 12 of these events appear to have been water hammers. Event 11 may have been a pump vibration incident rather than a water hammer. Additionally, one or several water hammer events may have occurred at Zion 1 prior to event 39.

Eight events (6, 7, 8, 12, 13, 31, 38, and 40) were attributed to feedwater control valve instability. Event 24 resulted from steam-bubble collapse, event 39 was attributed to isolation valve opening and the causes of two events (32 and 34) are unknown.

A review of the LER for event 39 indicates that an additional water hammer(s) may have occurred. Event 39 occurred after the feedwater line had been isolated to repair insulation and hanger damage and sag in the feedwater line. The damage reported in the LER indicates that one or more moderate to large water hammers of unknown type may have occurred, prior to event 39, causing this damage.

5.1.2.2 Water Hammer Causes

5.1.2.2.1 Feedwater Control Valve

The major cause of water hammer events in the feedwater systems is feedwater control valve (FCV) instability. FCVs contributed to eight of the ten system events for which a cause could be identified. The FCV instabilities resulted from such deficiencies as over-sizing of the valve, improper adjustment of the control circuitry, unbalanced valve trim and damage to the valve internal components.

A widespread problem in the design of feedwater systems is the division of responsibilities between the nuclear steam supply system (NSSS) vendor and the architect/engineer (AE). The NSSS vendor supplies and specifies FCVs. The AE designs the remainder of the condensate/feedwater system, from the condensate pumps to the steam generator. No one is specifically responsible for ensuring that FCVs are designed to be compatible with the remainder of the system. This lack of defined responsibility, combined with inadequate communications, has resulted in several designs in which the FCV is incompatible with the remainder of the feedwater system. The incompatibility problem is especially severe for systems containing motor-driven feed pumps, because such systems have very high FCV pressure drops at reduced plant loads. The high pressure drops at low flows tends to decrease valve stability. Systems containing turbine-driven feed pumps are more stable because feedwater flow is partially controlled by varying turbine speed.

The corrective measures taken by the plant for events 38 and 40 indicate uncertainty as to the cause of water hammer. The reported corrective action of limiting auxiliary feedwater flow to 50 gpm is a steam generator water hammer (SGWH) corrective measure and not a flow control valve corrective measure. SGWH is not in the scope of this investigation, but it is noted that the reported corrective measures are in accordance with a provision of Branch Technical Position ASB 10-2. If events 38 and 40 are control valve problems, the recommendation for event 6 would have been appropriate.

5.1.2.2.2 Other Causes of Water Hammer

Event 11 was probably not a water hammer because mixing of cold condensate with hot condensate cannot cause water hammer. The problem may not have been water hammer but could have been vibrations caused by condensate, or feedwater pump instability caused by pressure and flow fluctuations in the feedwater pump suction line. A temporary reduction in suction flow during valve switching can cause pump cavitation. If there were voids in the condensate systems, the feedwater pump should have tripped on low net positive suction head (NPSH) prior to void formation. Inadequate NPSH in feedwater suction lines can cause excessive pump vibrations prior to void formation.

The LER reports that event 39 occurred when the isolation valve in the feedwater line was opened to cool the feedwater line during cold shutdown. Slow opening of a valve is generally a correct procedure. However, the LER does not adequately define conditions upstream and downstream of the isolation valve to assess the cause of water hammer. Information required are fluid temperatures and pressures, both upstream and downstream of the isolation valve and in the steam generator, and the status of feedwater pumps and other pumps in connecting lines. Possibly, the use of a low-flow or bypass control valve for cooling may have been more appropriate.

Event 24 occurred when a valve was opened, allowing back-flow from the steam generator into an unpressurized feedwater cleanup line. The hot flow from the steam generator flashed in the unpressurized cleanup line downstream of a throttling valve, forming a steam bubble. Condensation of the bubble caused a steam-bubble-collapse water hammer.

5.1.3 Safety Significance

The safety significance of water hammer in feedwater systems is high, due to the large number of events (13), the large forces generated, and the potential for damage to safety-related equipment. The reported water hammer events in the feedwater system have resulted mostly in damage to the pipe support system components, instrument lines and supports. The feedwater lines are very large lines flowing at high velocities. Forces of several hundred thousand pounds can be generated from a water hammer. If flow control valve instability is not corrected, and water hammers recur, pipe or containment damage could result. (The feedwater lines are restrained at the containment.)

Damage to the feedwater line or its connecting lines can cause the loss of a steam generator for reactor core cooling, uncontrolled steam generator blowdown or loss of the auxiliary feedwater system, which is a safety-related system. Water hammer forces can also impose excessive stresses on the steam generator nozzles. This is significant in view of the history of cracks found in steam generator nozzles.

5.1.4 Recommendations for Prevention or Mitigation

5.1.4.1 Design Phase

a. Flow control valves should be selected that are properly sized, have balanced trim and are resistant to internal damage. FCV performance and response characteristics should be checked to ensure that valve instability will not occur at any operating condition.

b. The valve actuator should be designed to preclude rapid opening or closing under any possible (including spurious) control signal.

c. The organization specifying the design of the FCV should be responsible for the compatibility of the FCV with the rest of the feedwater system.

d. System design and procedures should be reviewed for the possibility of backflow from the steam generator through the main feedwater line to unpressurized lines, which could lead to water hammer due to steam-bubble formation and collapse.

e. A thorough design review should be made to identify all portions of piping in which voids or steam bubbles can form under any operating conditions. The operating conditions should include valve alignments that might occur during maintenance or through operator error.

f. Procedures should preclude the potential for steam or hot water entering unpressurized lines.

5.1.4.2 Operational Phase

a. Plants currently in operation should provide analysis to show that the FCV is compatible with the feedwater system design. A history of continued operation without FCV instability may be considered evidence of the adequacy of the FCV design. Where incompatibilities are found, appropriate corrective measures may include:

    o Modification of valve trim to lengthen valve stroke and provide balanced trim.

    o Controller modification to preclude rapid movement under a spurious signal.

    o Addition of hydraulic valve stem dampers that permit controlled valve motion but prevent rapid valve motion or oscillation.

- Changing feed pump impellers to reduce pump discharge pressure and thus FCV pressure drop. This will permit the FCV to operate in a more open position. This modification can have an additional cost benefit in some plants by saving one to two MWe used in providing unneeded pump head.

b. Feedwater valves and controllers should be inspected for evidence of cavitation, or damage and wear that could result in valve or controller failure. Appropriate repairs or replacements should be made as required.

c. The following design checks should be made during the preoperational phase:

   - Verify that control circuitry of the flow control valve is properly adjusted.
   - Verify that the FCV is properly sized.
   - Verify that the closing and opening times of the isolation and control valves are properly adjusted.
   - Check the operating procedures to ensure that all necessary lines can be properly filled during startup and remain filled during operation.

d. Any time the system is to be maintained or aligned in a manner not covered by existing procedures, an evaluation of water hammer potential and venting requirements should be made.

5.2 Reactor Coolant System Pressurizer

5.2.1 System Description

The pressurizer is a tank containing saturated water and steam. It is the point in the reactor coolant system (RCS) where liquid and vapor can be maintained in equilibrium under saturated conditions for pressure control purposes. The pressurizer surge line connects the pressurizer to one reactor hot leg, thus enabling continuous coolant volume and pressure adjustments between the RCS and the pressurizer. The surge line nozzle and electric heaters are located in the bottom of the pressurizer.

Spray line nozzles and relief and safety valve connections are located in the top head of the pressurizer vessel. Spray flow is modulated by automatically controlled valves.

Some plants have safety/relief valves only, while others have power-operated relief valves and safety valves. Power-operated relief valves limit system pressure and thus prevent actuation of the high-pressure reactor trip. The relief valves are operated either automatically or manually. The operation of these valves also limits the undesirable opening of the safety valves. The safety valves are spring loaded and self-activated with back-pressure compensation. Water seals are normally provided at the inlet of the pressure relief valves and safety valves to prevent leakage and erosion. The relief valve water seal is provided by sloping the valve inlet line. The safety valve seal is provided by a loop upstream of the valve.

The pressurizer relief discharge system collects and cools or condenses the water and steam discharged from safety and relief valves. The system consists of the pressurizer relief tank, the safety and relief valve discharge piping, the relief tank internal spray header and associated piping, the tank nitrogen supply, the vent to containment, and the drain to the waste processing system.

The pressurizer relief tank normally contains water and a predominantly nitrogen atmosphere. To obtain effective condensing and cooling of the discharged steam, the tank is installed horizontally with the steam discharged through a sparger pipe located near the tank bottom and under the water level. The sparger holes are designed to ensure that steam velocity is approximately sonic.

5.2.2 Water Hammer Evaluation

5.2.2.1 Event Review

The RCS pressurizer was involved in five of the PWR water hammer events reported in reference 1. These events are summarized in table 5-2. All the events occurred in the pressurizer relief discharge line. These events are not the classical, unanticipated "flow-into-voided-line" type of water hammer, in which the kinetic energy of the water slug is converted into pressure upon sudden stoppage at a closed end (valve or water front). Rather, they represent anticipated hydraulic transients, in which forces are generated by a pressure wave passing through the discharge piping following relief valve opening. The momentum changes caused by the presence of a water slug from the valve inlet water seal in each relief valve can increase the magnitude of these forces in the valve discharge lines. However, due to the area ratio of about 1:10 from the valve inlet to the common discharge line, the effects of the water slugs are greatly reduced in the common discharge header.

In PWR plants, the relief line piping upstream of the relief valves is designed to provide an upstream water seal against the valve seats. Events 10 and 33 occurred when the relief valves opened and the water slugs moved through the voided discharge piping at high velocity into the pressurizer relief tank without vaporizing. A hydraulic transient similar to events 10 and 33 could have occurred in event 1.

In events 15 and 22, damage occured in the pressurizer relief tank and not in the pressurizer relief discharge line. The relief tank rupture disc blew open in both events, indicating excessive pressure buildup in the relief tank. Neither events 15 nor 22 appear to have been water hammer events. The water originating in the pressurizer relief discharge line should not overpressure the relief tank. Normal level swell phenomenon is unlikely to have caused these events (events 15 and 22), as it would have been noticed in all pressurizer relief valve actuations. Excessive pressure buildup in the relief tank can be caused by the following:

- Insufficient cooling capacity due to low water level and/or high water temperature in the relief tank.
- Continuous blowdown or several sequential blowdowns that exceeded the tank cooling capacity.

In event 22, a minor system transient occurred which resulted in the opening of the pressurizer relief valve. In this event, the pressure relief valve stuck in open position due to boric acid crystal buildup, and RCS depressurization continued until the isolation valve was closed. In event 15, no cause for excessive blowdown was identified.

5.2.2.2 Water Hammer Causes

Three of the five reported events in the RCS pressurizer were normal hydraulic transients caused by relief valve discharge, possibly combined with additional momentum forces due to water slugs being propelled through the pressurizer relief discharge line into the relief tank at high velocities without vaporizing. It should be noted that, whenever the relief valves open, similar hydraulic transients with water slugs will occur in the discharge lines. Additionally, in discharge lines without vacuum breakers, when the discharge line cools off and steam condenses in the line, a vacuum may be formed and pull water up into the line from the relief tank. In a subsequent valve actuation, the additional water in the line will contribute to the transient hydraulic forces. Some plants have small holes in the pressure relief tank sparger above the water line to prevent vacuum formation.

It is noted that all events occurred prior to commercial operation, except event 22, in which a relief valve stuck open, and possibly event 33, which was noted by observation of damage a few weeks after the start of commercial operation. This indicates that the pipe support system designs have been adequate in most PWR plants. The inadequate designs were detected early and corrected. Preventive measures can involve a combination of actions: valve selection, valve inlet design modifications, adequate pressurizer relief discharge piping supports, and proper inspection and maintenance procedures.

Although no events were reported in reference 1, a more severe problem could be a safety valve loop seal water slug impacting a safety valve in those designs in which there is a long run of line between the loop seals and the safety valves.

5.2.3 Safety Significance

Water hammer has not been of safety significance in RCS pressurizer systems because no water hammers have occurred in the system. The safety significance of the pressurizer and the relief valve transients that have occurred in the system are moderate. The RCS pressurizer is a safety-related system. The pressurizer relief valves are used when temporary pressure transients occur in the pressurizer. The relief valves are expected to lift about ten times per year in a typical plant. Loss of pressurizer relief capability due to the valve damage or discharge piping damage would force the plant to shutdown. Stuck-open relief valves could lead to uncontrolled blow-down of the reactor coolant system if the block valve failed to close.

5.2.4 Recommendations for Prevention or Mitigation

5.2.4.1 NUREG-0737 Task II.D.1

NUREG-0737 (reference 2) task II.D.1 is concerned with demonstrating by testing and analysis that the relief and safety valves, block valves and associated piping in the reactor coolant system are qualified for the full range of operating and accident conditions. Task II.D.1 delineates the test requirements. EPRI is conducting an extensive test series on pressurizer safety and relief valves (generic program). Utilities will be required to account for the effects of discharge lines on valve operability (reference 2). Analysis will be based on EPRI test results. The reported events were not unanticipated water hammers but anticipated hydraulic transients. Therefore, if the lines and valves are tested and analyzed in accordance with reference 2, they should withstand the effects of valve opening transients.

5.2.4.2 Design Phase

a. Relief valve inlet seal loops and lines should be as short as possible to reduce the volume of the water slug.

b. The safety valve inlet seal loop should be placed immediately against the valve.

c. The design of the pressurizer relief valve discharge line and its support system should account for all loadings. Transient forces in SRV lines are unavoidable, and the design must consider such forces to be an anticipated event in accordance with references 2, 3 and 4.

d. A vent hole should be installed in the discharge line inside the relief tank, but above the relief tank water level, to prevent vacuum formation in the discharge line.

e. Heat tracing and insulation may be installed on the relief valve inlet water seal so that a portion of the seal water will flash when discharged through the pressurizer relief discharge line into the relief tank. This will reduce transient forces to some extent.

5.2.4.3 Operational Phase

The following design checks should be made during the preoperational phase:

a. Adequacy of the valve inspection and maintenance procedures should be verified.

b. The adequacy of the pipe support system inspection and maintenance procedures should be verified.

c. Operating plants are required to conform to the provision of NUREG-0737 task II.D.1, discussed in section 5.2.4.1. If a hydraulic transient occurring during the operational phase causes damage, the severity of the event should be assessed and appropriate corrective measures taken.

5.3 PWR Main Steam System

5.3.1 System Description

The main steam system supplies steam from the steam generators to the turbine-generator system. The system consists of main steam piping, power-operated relief valves, safety valves, turbine stop valves, and main steam isolation valves. It also provides steam to such systems as the turbine-generator system second stage reheaters, the main feed pump turbines and the auxiliary feed pump turbine, the steam seal system, the turbine bypass system, the auxiliary steam reboiler, the process sampling system, and condenser spargers.

5.3.2 Water Hammer Evaluation

5.3.2.1 Event Review

Table 5-3 presents the eight PWR main steam system water hammer events reported in reference 1. Only six of these events (3, 17, 18, 21, 30 and 35) occurred in the main steam system. Reference 1 included one event (37) in the auxiliary feedwater pump turbine exhaust line and one event (16) in the steam generator blowdown line with the main steam system for convenience of reporting.

5.3.2.1.1 Main Steam System Events

Event 3 was the only main steam system event that was an unanticipated water hammer. In event 3, the main steam isolation valves were inadvertently opened and admitted steam into a partially warmed main steam line during heatup. There was no reported damage.

Four events (17, 18, 30 and 35) in the main steam system were anticipated steam hammers resulting from valve closure. It should be noted that the isolation valves and turbine stop valves in the main steam line are designed to close rapidly, and the piping system should be designed to withstand the resulting steam hammer.

Event 21 caused damage to two hydraulic suppressors on the main steam relief valve line which was observed during routine inspection. The damage appears to have been caused by the high reaction forces that normally result from relief valve actuation rather than by a water hammer.

5.3.2.1.2 Other Events

Event 37 was a steam-water entrainment event that occurred in the AFW turbine exhaust line. The event damaged a hanger.

Event 16 ocurred in the steam generator blowdown piping and resulted in failure of a snubber pipe clamp, breakage of a spring hanger support rod, and a crack in the shell drain.

5.3.2.2 Water Hammer Causes

Four of the six steam (water) hammer events occurring in the main steam system (17, 18, 30, and 35) were caused by valve closure. The valve closures were attributed to spurious signals in events 17 and 35. In event 18 the excess flow check valve failed closed due to flutter. The cause of valve closure was unidentified in event 30. The steam hammers resulting from such valve closures are similar to those resulting from anticipated valve closure events, and the piping supports should be designed to withstand dynamic loads resulting from valve closure. These events should not be considered as unanticipated preventable steam hammers.

Event 3 was the only true anticipated water hammer in the main steam lines. It was caused by inadvertent opening of the main steam isolation valves and the resulting admission of steam into a partially warmed main steam line, due to poor operating procedure. The lack of proper warm-up caused condensation of steam, creating a water slug. The water slug caused a steam-water entrainment water hammer when it impacted a closed turbine stop valve.

In event 21, there was no indication of water hammer, but this event resulted in damage to two hydraulic suppressors on the main steam relief valve line due to inadequate design and improper installation of the supports.

Event 37 was caused by steam-water entrainment in the steam-driven turbine exhaust drain line of the auxiliary feedwater pump. The cause of the water hammer was attributed to an inadequate design that permitted rain water to enter the exhaust piping and to poor maintenance of the piping drain system.

Event 16 occurred in the steam generator blowdown line, which returns steam generator blowdown to the condenser. The water hammer could have been caused by opening the valve too rapidly. The standard procedure is to crack the valve to warm up the line, then slowly open the valve.

5.3.3 Safety Significance

5.3.3.1 Main Steam Systems

Water hammer in PWR main steam systems is of low safety significance. In the only unanticipated event there was no reported damage. The anticipated steam hammers and relief valve discharge incident resulted in either no damage or minor support damage.

The main steam lines are safety-related up to and including the main steam isolation valve. The main steam relief valves are a safety-related means of removing the reactor heat. The reported water hammer events in the main steam system resulted in damage to the pipe support system components. No events occurring in the main steam lines have been severe enough to cause piping damage.

5.3.3.2 Auxiliary Feedwater System

Auxiliary feedwater (AFW) is a safety-related system. However, there have been no significant water hammer events in this system; therefore the safety significance of water hammer in the AFW system is low. The only water hammer event occurring in the AFW system caused damage to an AFW turbine exhaust line hanger. This damage can not affect the system operation.

5.3.3.3 Steam Generator Blowdown System

Water hammer in the steam generator blowdown (SGB) system is of low significance. Only one event has been reported in steam generator blowdown systems. The system performs no safety-related function and consists of small lines. The worst possible effect of an SGB water hammer would be a small secondary system leak.

5.3.4 Recommendations for Prevention or Mitigation

5.3.4.1 Design Phase

a. The design bases of pipe support system components in the main steam lines and other connecting lines should include potential steam hammer dynamic loads resulting from valve closure. The planned rapid closure of turbine stop valves makes occurrence of steam hammer unavoidable. Steam hammers in the main steam system are of lesser magnitude than water hammers, due to lower fluid density and higher compressibility. The lower magnitude of steam hammer forces compared to water hammer forces make the pipe support designs for these loads practical. Designing for these loads is required by references 3 and 4.

b. Design of the steam-driven turbine exhaust drain line piping should preclude back pressure buildup, such as from accumulation of condensate and rain water.

c. System design and operating procedures should be reviewed for possibility of water entrainment in steam lines during startup.

d. Valves in the main steam system should be designed to withstand normal and emergency operating conditions.

e. Pipe supports in the main steam relief valve lines should be designed for the relief valve discharge loads.

5.3.4.2 Operational Phase

a. Pipe support system components should be inspected during refueling outages for evidence of wear and damage. Appropriate repairs or replacements should be made when required.

b. The auxiliary feedwater pump turbine drain system traps should be periodically checked and maintained.

c. Any time the system is to be maintained or aligned in a manner not covered by existing procedures, an evaluation of water hammer potential and venting requirements should be made.

5.4 PWR Residual Heat Removal System

5.4.1 System Description

The residual heat removal (RHR) system is called the decay heat removal system in some plants. The primary function of the RHR system is to remove decay heat from the fuel and the reactor coolant system (RCS) during plant shutdown and refueling operations, and, in a majority of PWR plant designs, following a loss-of-coolant accident. The RHR system may also be used to transfer refueling water between the refueling cavity and the refueling water storage tank at the beginning and end of refueling operations.

The system consists of two mutually redundant trains of heat exchangers and pumps, located in the plant's lower elevations and associated piping, and valves and controls that cool and circulate reactor coolant water through the RCS. The most severe system operating condition is 400 psig and 350°F, which occurs during the start of plant shutdown cooling. The RHR system is normally aligned to take suction from the RWST. There are system connections to the RCS that are isolated during normal plant operation. There are also connections to ambient temperature water sources and the refueling water system.

During normal plant shutdown, operation of the RHR system is initiated when reactor coolant temperature has been reduced to 350°F and 450 psig or less. The block valves in the lines to the RCS are opened and the RHR pumps started. The RHR system cools the RCS by circulating reactor coolant through the RHR heat exchangers (Hx). The RHR continues to operate after the reactor vessel is opened and refueling operation proceeds.

Following a LOCA, reactor coolant and borated refueling water which has collected in the containment sump is pumped by the RHR pumps through an RHR Hx to the hot legs of the RCS. Recirculation is initiated manually when the borated water in the refueling water storage tank (RWST) falls below a predetermined level.

5.4.2 Water Hammer Evaluation

Only one water hammer event (25) was reported in reference 1 in a PWR RHR system. That event is summarized in table 5-4. However, the RHR system is generically susceptible to the types of water hammer events that occur in normally idle pumped water systems, such as flow into voided lines in the pump discharge lines and steam-bubble collapse in the high-temperature pump suction lines during the start of shutdown cooling.

Event 25 occurred during a refueling shutdown when an RHR pump was started. The event was probably caused by flow into a voided line. The voiding may have been initiated by an incorrect valve lineup before the pump start.

The PWR RHR system is less prone to voiding than similar BWR systems. The level of the water source in the reactor water storage tank is above the pump discharge line and serves as a keep-full system. Therefore, the design of the system makes void formation by leakage during standby unlikely. The main potential for void formation occurs during outages and maintenance operations.

5.4.3 Safety Significance

The safety significance of water hammer in the PWR RHR systems is low because the one event that occurred in the system only resulted in support damage. The RHR is a safety-related, operator-initiated system. The system has redundant active capacity. The redundant trains of the systems, however, share some common lines. The system is connected to the primary coolant pressure boundary. Inspection of the system can be performed during plant operation, and is done during surveillance testing.

5.4.4 Recommendations for Prevention or Mitigation

5.4.4.1 Design Phase

a. A vent system should be provided that vents all portions of the piping. All venting should be at the line high point. Any portion of piping isolated from the system high point by a valve should have a separate vent point.

b. The vent system should be remotely operated or designed and located to maximize the ease of line venting during fill operations.

c. A design review should be made that identifies all portions of piping in which voids or steam bubbles can form under any operating condition, including off-design valve or standby alignments that might occur during maintenance or through operator error.

5.4.4.2 Operational Phase

a. The system should be considered inoperable when voids are present in the piping. The system still will be available for emergency use.

b. Any time the system is to be maintained or aligned in a manner not covered by existing procedures, an evaluation of water hammer potential and venting requirements should be made.

5.5 ECCS Safety Injection System

5.5.1 System Description

The ECCS safety injection system supplies borated water to the reactor coolant system (RCS) for cooling and reactivity control. The safety injection system consists of several independent subsystems that provide equipment and flow path redundancy to cover all possible break sizes. The subsystem equipment consists of pumps, piping, accumulators, borated water storage tanks, and associated controls with varying configurations depending on the PWR manufacturer.

The system has two subsystems, passive accumulator injection and active safety injection.

In the passive accumulator injection subsystem, low-temperature borated water, stored in accumulator tanks at approximately 650 psi, is injected into the RCS when the system pressure falls below 650 psi.

The accumulators are pressurized with nitrogen gas to maintain 650 psi and are connected to the RCS by piping containing check valves and normally open valves.

Active safety injection is performed by the low head and high head safety injection systems. The high head safety injection system generally uses the chemical volume control system (CVCS) charging pumps, which supply borated water to the RCS at high pressure for small breaks. The low head safety injection system (LHSI) supplies borated water to the RCS for large breaks in which the reactor pressure decreases rapidly. In some plants the LHSI uses the RHR pumps. The LHSI pumps are aligned to take suction from the refueling water storage tank (RWST).

5.5.2 Water Hammer Evaluation

A summary of PWR safety injection system water hammer events reported in reference 1 is provided in table 5-5. Four different plants were involved in the four events. Three of the events (23, 26 and 29) occurred in active safety injection subsystems during testing or plant operation and were classified as flow-into-voided-line events.

Event 23 was caused by poor procedures, which resulted in air being introduced into the LHSI pump suction line during sodium hydroxide filling operations. This event is plant specific, since the interconnecting lines and valving apparently allowed air to be introduced into the low pressure safety injection suction line. The filling operation was performed during a cold shutdown so that plant safety was never involved.

Events 26 and 29 were attributed to inadequate design and/or procedures that involved poor venting and filling.

The fourth event (34) was a steam-bubble collapse water hammer in an accumulator discharge line to the RCS. The cause of this event was poor testing procedures that allowed the line pressure to drop below saturation pressure during leak testing. This implies the occurrence of either a large leak of hot water through the check valve from the RCS, the pulling of a slight vacuum in the line during the leak test, or excessive testing (venting) in combination with a moderate check valve leak.

Three of the events (23, 26 and 29), all flow-into-voided-line events, occurred three to seven years after the start of commercial operation. The steam bubble collapse event (34) occurred a year after the start of commercial operation.

5.5.3 Safety Significance

5.5.3.1 Accumulator Injection

The safety significance of water hammer in the accumulator injection subsystem is low. The one event in this subsystem resulted from testing that is only performed during shutdown and caused only minor support damage. The subsystem is safety-related as a part of the ECCS and automatically supplies borated cooling water to the RCS when the RCS pressure falls below the accumulator pressure. One accumulator is normally provided for each RCS loop, and the flow discharges into either an RCS cold leg or the reactor vessel. The subsystem is tested during plant operation and can be inspected during plant shutdown.

5.5.3.2 Active Safety Injection

The safety significance of water hammer in the active safety injection subsystem is high. The three events in this system caused considerable support damage. One event placed six supports in a faulted condition.

The subsystem is safety-related and are automatically actuated as a part of the ECCS, following a safety injection signal. The subsystem is connected to the RCS pressure boundary and to containment penetrations. It is tested and can be inspected during plant operation.

5.5.4 Recommendations for Prevention or Mitigation

5.5.4.1 Design Phase

a. A vent system should be provided that vents all portions of the piping between the pump discharge and the RCP boundary. All venting should be at the line high points. Any portion of piping that is isolated from the system high point by a valve should have a separate vent point.

b. The vent system should either be automatic, remotely operated or designed and located in a manner to maximize ease of line venting.

c. A monitoring and alarm system should be provided to detect voids. The system should be considered inoperable when voids are present in the piping. The system will still be available for emergency use.

d. A thorough design review should be made that identifies all portions of piping in which voids or steam bubbles can form under any operating conditions. The operating conditions should include valve alignments that might occur during maintenance or through operator error.

e. Procedures should be reviewed to eliminate any possiblity of introducing air into lines during filling operations. Valve lineup requirements in individual system operating procedures should be written to preclude conditions conducive to water hammers, such as voided sections of piping.

f. Procedures should be reviewed to insure that line pressure is maintained at a level above the saturation pressure to prevent formation of steam voids in lines by water flashing during leak testing.

5.5.4.2 Operational Phase

a. Valves should be leak checked periodically. When projected valve leakage is deemed to be large, repairs or replacements should be made.

b. Any time the system is to be maintained or aligned in a manner not covered by existing procedures, an evaluation of water hammer potential and venting requirements should be made.

5.6 Chemical and Volume Control System

5.6.1 System Description

The chemical and volume control system (CVCS) adds makeup water to the reactor coolant system, removes and reprocesses water from the reactor coolant system, provides seal water injection to the reactor coolant pump seals, adjusts the concentration of boric acid for chemical reactivity control, maintains a proper concentration of corrosion-inhibiting chemicals and keeps the reactor coolant fission product and corrosion product activities within design limits.

During plant operation, reactor coolant flows through the letdown line, from the reactor coolant system cold leg to the shell side of the regenerative heat exchanger (RHx), where its temperature is reduced. The coolant then flows through letdown orifices which reduce the coolant pressure. The cooled, low-pressure water leaves the reactor containment and enters the auxiliary building where it undergoes a second temperature reduction in the tube side of the letdown heat exchanger followed by a second pressure reduction by the low-pressure letdown valve. After processing, the coolant is returned by the charging pumps through the tube side of the RHx to the reactor coolant system. Because of large changes in temperature and pressure conditions, the occurrence of water hammer is possible in the letdown part of the CVCS.

5.6.2 Water Hammer Evaluation

5.6.2.1 Event Review

Table 5-6 presents a summary of the two chemical and volume control system water hammer events reported in reference 1. One event was reported as being caused by steam-bubble collapse and the other by flow into voided line. Both events occurred in the letdown line. When using these data for cause evaluation, it should be noted that water hammer was not actually observed in either of these cases. The previous occurrence of water hammer was surmised on the basis of observed damage. As an example, event 19 might have been caused by inadequate tightening of valve positioner bolts and consequent line vibration.

5.6.2.2 Water Hammer Causes

Possible mechanisms of water hammer occurrence are discussed below: An interruption or reduction of charging pump flow through the RHx will cause the exit temperature of the letdown flow to rise. If the letdown temperature is too high, flashing can occur when pressure is reduced on the downstream side of the letdown orifice, causing formation of steam bubbles. Subsequent collapse of the steam bubbles upon contact with cooler water can cause a water hammer event. Events 19 and 27 could have been caused by this scenario. However, this is not considered likely, for the following reasons. The RHx has a large thermal capacity with respect to letdown flow. Furthermore, a low charging flow alarm and letdown pressure and temperature indicators are available to alert the operator to take action should the temperature in the line rise. In some recent plant designs a temperature controller is provided in the letdown line.

In some plants it has been observed that the letdown line normally vibrates extensively. Equipment damage could have been caused by continuous vibration rather than a single water hammer event.

In particular, the damage noted in event 19 could have also been caused by vibration, in combination with an improperly installed valve positioner, rather than by water hammer. If the valve positioner bolts were inadequately tightened, normal line vibrations could cause the positioner to fall off, damaging the instrument air line. The resulting loss of signal to the controller can result in increased line vibrations due to flow oscillations. These vibrations could have caused the observed pressure tap and drain line damage without the occurrence of water hammer.

5.6.3 Safety Significance

The safety significance of water hammer in chemical and volume control systems is low. The only portion of the chemical and volume control system in which water hammer has been reported is in the letdown lines, which do not perform any safety function, but are connected to the reactor coolant boundary. The safety injection and emergency boration functions of the CVCS are covered under the ECCS (section 5.5). None of the two reported events damaged piping inboard of the letdown line isolation valves.

5.6.4 Recommendations for Prevention or Mitigation

5.6.4.1 Design Phase

a. A thorough design review should be performed to identify all portions of piping in which voids or steam bubbles can form or collapse under any operating condition, including valve alignments that might occur during maintenance or through operating error.

b. A high-temperature alarm should be incorporated in letdown lines, to provide the operator with sufficient time to prevent flashing from occurring at the downstream side of the letdown orifice.

c. Venting facilities should be provided at the system high points. Any portion of piping that is isolated from the system high point by a valve should have a separate vent point.

5.6.4.2 Operational Phase

Any time the system is to be maintained or aligned in a manner not covered by existing procedures, an evaluation of potential water hammer conditions and venting requirements should be performed.

5.7 PWR Condenser System

5.7.1 System Description

The main condenser is the steam cycle heat sink. During normal operation, it receives and condenses main turbine exhaust steam, steam generator feedwater pump turbine exhaust steam, and turbine bypass steam. The main condenser is also a collection point for other steam cycle miscellaneous flows, drains, and vents. Hotwell level controls provide automatic makeup or rejection of condensate to maintain a normal level in the condenser hotwells. The noncondensable gases contained in the turbine exhaust are collected in the condenser and removed by the condenser air removal system. The condensate pumps take suction from the condenser hot wells and pump water through heaters to the feedwater system.

5.7.2 Water Hammer Evaluation

Three out of the four PWR condenser system events reported in reference 1 and summarized in table 5-7 occurred in the condenser. The other event (14) caused damage to the main condensate line. Of the four events, one (14) was a water hammer and three (events 2, 4, and 5) appear to have been normal hydraulic transient events resulting from discharge valve opening, which occurred prior to or just after commercial operation. Damage was caused by inadequate design of some components inside the condenser. It should be noted that damage from events 2, 4, and 5 did not occur on or in fluid-carrying lines, but appeared to be the result of jet forces from the fluids leaving the lines. Event 2 was the result of turbine bypass transient flow, which caused damage to turbine bypass spargers and several other components inside the condenser, such as impingement plates, tie rods, and expansion joints. Events 4 and 5 appear to have been hydraulic transients in the heater drain tank line to the condenser, which were caused by valve opening. Event 4 was the first of two similar events, resulting in damage to the flow deflector inside the condenser. Some of the condenser tubes were damaged by a portion of the torn deflector. The cause of the damage in events 4 and 5 appears to have been inadequate design of deflector plate inside the condenser. Design inadequacies in these three events were detected early and corrected.

Event 14 was a water hammer that may have been caused by inadequate design of the main condensate deaerator level regulating valve and the piping arrangement. The damage occurred after seven years of operation. Direct contact heaters such as deaerators, and their attached lines, frequently experience hammering, level control and vibration problems. The damage observed in event 14 could have been the result of several vibration or water hammer incidents rather than a single incident.

5.7.3 Safety Significance

The safety significance of water hammer in condensate and condenser systems is low. The systems have no safety-related functions. The failure of the main condenser will not preclude operation of any essential system. Generally, no safety-related equipment is located in the turbine building, where these systems are located. Protection against the effects of pipe ruptures is not a water hammer concern but a pipe rupture concern. This protection should have been provided for those few plants that have safety-related equipment in the turbine building, in accordance with SRP 3.6.1.

5.7.4 Recommendations for Prevention or Mitigation

5.7.4.1 Design Phase

a. Select level-regulating valves that have durable components and good performance characteristics.

b. Develop inspection and maintenance procedures for level-regulating valves.

c. Design piping arrangements that will minimize the potential for water hammer.

5.7.4.2 Operational Phase

a. The operational characteristics of the valves and controllers should be verified.

b. The level-regulating valves should be periodically inspected and tested to ensure that they are in good working condition. Valve control and operational instabilities or other problems should be noted and corrected. Appropriate repair or replacement should be made when required.

5.8 PWR Cooling Water Systems

This section evaluates water hammer events occurring in PWR cooling water systems that have impact on plant safety. These systems include service water and component cooling water systems.

5.8.1 System Description

The service water and component cooling water systems provide essential cooling to safety-related equipment and may also provide cooling to nonsafety-related auxiliary components that are required for normal plant operation.

The service water system is an open-loop system consisting of two or more pumps taking suction from the ultimate heat sink. The essential loads are provided by two mutually redundant cooling water trains, supplied by loop headers coming from the main supply header. The nonessential loads are supplied from separate branch headers that can be isolated from the main headers under accident conditions.

The component cooling water system is a closed-loop, dual-train, solid-water system with two or more pumps in each train. Redundant heat exchangers cooled by the service water system provide cooling. A surge tank is connected to each suction header. The pumps discharge into a header. There are valves installed in the cross-connect lines and at the inlet of major branching sections of each header so that each train can be isolated. In the event of a loss-of-coolant accident, one pump and one heat exchanger are capable of fulfilling system requirements.

5.8.2 Water Hammer Evaluation

5.8.2.1 Event Review

Table 5-8 presents a summary of the three PWR cooling water systems water hammer events reported in reference 1. Events 9 and 20 were reported as flow-into-voided-line events. Event 28 is considered a report of a structural failure rather than water hammer event because no piping forces were generated. When using this data, it should be noted that water hammer was actually observed in event 20 only.

5.8.2.2 Water Hammer Causes

During standby periods, the temperature of cooling water entrapped in an isolated component drops, causing the water to shrink in volume. This shrinkage then creates voids filled with gases and water vapor. On subsequent opening of the isolation valves, cooling water flow then surges into the partially voided line creating a water hammer. Event 9 could have been caused by this scenario. In a closed-loop system it is common procedure to isolate only the inlet valves on components such as heat exchangers when removing them from service. This practice permits water from the surge tank to make up component cooling water volume lost by cooling. Problems occur when this procedure is not followed, or if both the inlet and outlet valves are closed for maintenance. If both valves are closed, venting procedures must be closely followed to prevent voids in the system.

Flow into voided line may also have been the cause of event number 20. On open-loop systems, such as service water to the diesel generator, the flow may be controlled through a component by its outlet valve. When a component is put into service, a solenoid valve de-energizes, allowing air to open the flow control valve. This arrangement provides a fail-safe mode to ensure cooling flow in the event of a component electrical failure. It is possible, though, that when maintenance is performed on the component or control breaker with no flow in the system, the solenoid valve can be de-energized, allowing the line to drain and create a void. This would require special precautions when returning the system back to service to ensure proper venting.

5.8.3 Safety Significance

The safety significance of water hammer in PWR cooling water systems is moderate. Neither of the two events rendered a system inoperable. One of the events, which occurred while the plant was in construction, damaged the inlet nozzle to a diesel generator air cooler water box. Safety-related cooling water systems provide cooling water to many safety-related systems. Loss of cooling water can disable trains of many systems. The safety-related cooling water systems have redundant trains. However, they often share common headers. The systems are tested regularly and can be inspected during plant operation.

5.8.4 Recommendations for Prevention or Mitigation

5.8.4.1 Design Phase

a. A design review should be performed to identify all portions of piping in which voids or column separation could occur under normal operating conditions or infrequent off-normal valve line-ups.

b. A vent system should be provided for all components in which it is possible to trap air during maintenance.

c. Procedures for venting the system should consider all portions of the piping system, including heat exchangers and their water boxes, under both normal and off-normal valve line-ups for maintenance.

d. A monitoring and alarm system should be incorporated to detect void formation.

5.8.4.2 Operational Phase

a. To avoid potential water hammer situations, cooling water flow to a previously isolated component should be restored gradually. In a closed-loop system the outlet valve should be slowly opened so that the voided portion can be filled from the surge tank. Proper venting procedures should be followed.

b. Valves should be leak tested periodically. When projected valve leakage is deemed to be large, repairs should be made.

c. Anytime the system has maintenance performed, or is aligned in a manner not covered by existing procedures, an evaluation of possible water hammer conditions and venting requirements should be performed. Attention should be given to automatic valves that may have operated due to control breaker maintenance.

NOTE 1: No water hammer was actually
witnessed. The occurrence
of a water hammer was reported
based upon observed damage.

Table 5-1 WATER HAMMER EVENTS IN PWR FEEDWATER SYSTEM

EVENT NO.	PLANT/ DESIGN	COM. OP. DATE	EVENT DATE	OPERATING MODE	WATER HAMMER TYPE	MECHANICAL FUNCTION	INITIAL INDICATION/ DAMAGE	CAUSE AND EVENT BASIS	COMMENTS
24	Rancho Seco B&W	4/17/75	1974	Hot functional testing	Steam bubble formation and collapse	FCV throttling	Water hammer noise. Seismic support was damaged.	Inadequate design. Valve lineup allowed back flow from SG through FW inlet line, into FW cleanup line, and then flashing into condenser when valve throttling reduced inlet line pressure.	Check system design and procedure for probability of back flow for all functional conditions.
6	Beaver Valley-1 W	4/30/77	11/5/76	50% Power	Unknown (water hammer due to wave reflection)	FCV instability in auto mode	Water hammer noise and variations in steam generator water level. Damage occurred to instrument lines, valves, insulation, fittings, and shock suppressors.	Inadequate design. Sudden flow oscillations probably due to FCV oscillations.	Extensive system analysis and re-design of FCV.
7	Beaver Valley-1 W	4/30/77	12/27/76	73% Power	Unknown (water hammer due to wave reflection)	FCV instability in auto mode	FW flow oscillations and FW system vibrations. Damage to instrument lines and support.	Inadequate design. Unstable FCV allowed valve opening inappropriate to control signal.	Extensive system analysis and re-design of FCV.
8	Beaver Valley-1 W	4/30/77	1/5/77	74% Power	Unknown (water hammer due to wave reflection)	FCV instability in auto mode	FW flow oscillations and FW system vibrations. Damage to instrument lines, drains, valves, supports, and related items.	Inadequate design. Unstable FCV allowed valve opening inappropriate to control signal.	Extensive system analysis and re-design of FCV.
11	Ginna W	3/70	6/71	At Power	Unknown	Turbine cycle, valve opening	Severe vibrations in the main FW pump suction lines. FW suction valve position indicator damaged.	Inadequate design and poor procedures. TCV fail closed while normal condensate bypass valve was in closed position. Emergency FW valve opened and relatively cold condensate supplied directly to FW pump suction.	May not have been water hammer.

NOTE 1: No water hammer was actually witnessed. The occurrence of a water hammer was reported based upon observed damage.

Table 5-1 (Continued) WATER HAMMER EVENTS IN PWR FEEDWATER SYSTEM

EVENT NO.	PLANT/ DESIGN	COM. OP. DATE	EVENT DATE	OPERATING MODE	WATER HAMMER TYPE	MECHANICAL FUNCTION	INITIAL INDICATION/ DAMAGE	CAUSE AND EVENT BASIS	COMMENTS
12	Ginna W	3/70	7/22/73	1455 MWt	Unknown (water hammer due to wave reflection)	FCV instability	Water hammer noise. cracked support adjacent to valve, skewed rod hanger supports, damaged FW pipe insulation.	Poor quality control. FCV valve plug separation induced flow oscillations.	Adhere to strict quality control for valve manufacturing.
13	Ginna W	3/70	6/75	Return to power	Unknown (water hammer due to wave reflection)	FCV instability	FW piping vibration. Pressure gauge tubing was broken. Vent valve vibrated partly open. Tubing pulled out of transmitter fitting. FW piping insulation was shaken loose.	Inadequate design. FCV instability in 30% to 40% load range.	Extensive system analysis and redesign of FCV.
31	San Onofre-1 W	1/1/68	5/14/79	Maintenance outage	Flow into line with closed valve	FW regulating valve closure	Audible indication. Damaged a snubber on main FW line.	Incorrect procedures or maintenance. Rapid valve closure due to misadjustment of valve control circuitry.	Require controller adjustment.
38	Zion-1 W	12/31/73	5/76	875 MWe	Unknown (probably water hammer due to wave reflection)	Unidentified (probably valve instability)	Water hammer noise. No damage (safety injection occurred).	Inadequate design. Rapid FW flow increase to SG due to water hammer, probably from rapid trim on FCV.	See Event 6. Auxiliary FW was limited to 50 gpm per SG as a corrective measure.
39	Zion-1 W	12/31/73	9/26/76	Cold shutdown	Unknown (probably water hammer due to wave reflection)	Valve opening	Water hammer noise. No damage due to water hammer (safety injection occurred).	Inadequate procedure. Water hammer occurred when isolation valve to FW line was opened slightly for cooling during cold shutdown.	Procedures should preclude the potential for steam and hot water entering unpressurized lines.
40	Zion-2 W	9/17/74	6/76	875 MWe (Hot shutdown)	Unknown (probably water hammer due to wave reflection)	Unidentified (probably valve instability)	Water hammer noise. No damage (safety injection occurred).	Inadequate design. Rapid FW flow increase to SG due to water hammer, probably from rapid trim on FCV.	See Event 6. Auxiliary FW was limited to 50 gpm per SG as a corrective measure.

NOTE 1: No water hammer was actually witnessed. The occurrence of a water hammer was reported based upon observed damage.

Table 5-1 (Continued) WATER HAMMER EVENTS IN PWR FEEDWATER SYSTEM

EVENT NO.	PLANT/ DESIGN	COM. OP. DATE	EVENT DATE	OPERATING MODE	WATER HAMMER TYPE	MECHANICAL FUNCTION	INITIAL INDICATION/ DAMAGE	CAUSE AND EVENT BASIS	COMMENTS
32	San Onofre-1 W	1/1/68	5/15/80	Unknown	Unknown	Unidentified	Damage observed during routine inspection. Three supports on FW line damaged.	Unknown mechanical loading and probably inadequate design.	Design of support system components should include consideration of potential water hammer dynamic loads.
36	Turkey Point-4 W	9/7/73	6/11/79	Unknown	Unknown	Unidentified	Damage observed during routine inspection. A snubber on SG overloaded.	Unknown meachanical loading and probably inadequate design.	See Event 32.

NOTE 1: No water hammer was actually witnessed. The occurrence of a water hammer was reported based upon observed damage.

Table 5-2 WATER HAMMER EVENTS IN PWR RCS PRESSURIZER

EVENT NO.	PLANT/ DESIGN	COM. OP. DATE	EVENT DATE	OPERATING MODE	WATER HAMMER TYPE	MECHANICAL FUNCTION	INITIAL INDICATION/ DAMAGE	CAUSE AND EVENT BASIS	COMMENTS
1	Arkansas-1 B&W	12/19/74	9/12/74	Power escalating testing	Relief valve discharge transient flow	Pressurizer relief valve opening	Excessive pipe movement readings. Several hanger rods were bent.	Probably inadequate pipe support design. Cause not given. Probably same as Event 10.	Effect of hydraulic transient with water slug from valve inlet water seal should be considered for piping design.
10	Davis-Besse-1 B&W	7/31/78	8/5/77	Hot functional testing	Relief valve discharge transient flow	Pressurizer relief valve opening	Severe movement of discharge piping. No damage.	Inadequate pipe support design. Piping upstream of relief valves holds a water seal against valves. When valves open, water slug is impelled through piping into relief tank unless vaporized. Forces through valve discharge possibly increased by momentum forces of slug. Damage caused by support design that was inadequate to withstand these forces.	Effect of hydraulic transient with water slug from valve inlet water seal should be considered for piping design.
15	Indian Point-2 W	8/73	5/13/74	Increasing power level	No indication of water hammer	Pressurizer relief valve opening	Sudden pressure reduction in pressurizer relief tank. Tank rupture disc blew open. Concrete grouting on tank pedestals was slightly cracked.	Unknown. Possible extensive blowdown into tank.	Note 1. No indication of water hammer. Probably pressure built up in relief tank to blow open the rupture disc.
22	Oconee-3 B&W	12/16/74	6/75	Power reduction to about 15%	No indication of water hammer	Pressurizer relief valve opening	Unexplained drop in RCS pressure. Tank rupture disc blew open. Mirror insulation separated from bottom nozzle of pressurizer. 1500 gallons of coolant were released to containment sump.	Inadequate valve maintenance. Pressurizer relief valve was stuck in open position due to boric acid crystal build-up.	Note 1. No indication of water hammer. Regular inspection and maintenance should be performed. Valve cycling should be part of the start-up procedure.
33	Surry-1 W	12/22/72	1/73	Unknown	Relief valve discharge transient flow	Pressurizer relief valve opening	Broken seismic snubber on discharge piping. Seismic snubber was broken due to displaced discharge line piping.	See Event 10.	Note 1. See Event 10.

NOTE 1: No water hammer was actually witnessed. The occurrence of a water hammer was reported based upon observed damage.

Table 5-3 WATER HAMMER EVENTS IN PWR MAIN STEAM SYSTEM

EVENT NO.	PLANT/ DESIGN	COM. OP. DATE	EVENT DATE	OPERATING MODE	WATER HAMMER TYPE	MECHANICAL FUNCTION	INITIAL INDICATION/ DAMAGE	CAUSE AND EVENT BASIS	COMMENTS
3	Arkansas-1 B&W	12/19/74	6/76	Heatup	Probably steam hammer due to wave reflection	Main steam isolation valve opening	Water hammer noise. No reported damage.	Poor operating procedure. Main steam isolation valves were inadvertently opened and admitted a slug of hot steam into partially warmed main steam line causing steam hammer.	Review system design and procedures for possibility of water entrainment in steam lines.
17	Maine Yankee CE	12/28/72	12/2/72	Unknown	Probably steam hammer due to wave reflection	Excess flow check valves closing.	Drop in SG pressure. No reported damage.	Personnel error. False signal caused steam dump valves to open, dropping SG pressure. Flow check valves then closed, causing sudden increase in SG pressure and thus initiating scram.	Steam dump valve signals were on transient recorder patch for testing. Personnel instructed to remove the signals from the patch panel and take utmost caution when connecting to the test recorder.
18	Maine Yankee CE	12/28/72	10/11/73	80% Power	Probably steam hammer due to wave reflection	Excess flow check valves closing (initiated by a spurious signal)	Low SG level. Valve internal damage.	Inadequate valve design. Repeated problems with valve flutter of damaged valve, which fail closed.	Note 1. Redesigned valve, which can withstand the normal and emergency operating conditions, should be used.
21	Oconee-1 B&W	7/15/73	6/28/79	Unknown	No indication of water hammer	Unknown	Damaged observed during 6/28/79 routine inspection. Damage to two hydraulic suppressors on the main steam relief valve line.	Inadequate design and improper installation of hydraulic suppressors.	Note 1. Forces were probably due to normal relief valve actuation.
35	Turkey Point-3	12/14/72	11/5/75	Probably at full power	Probably steam hammer due to wave reflection	Probably MSIV closure.	Distortion of spring support on MS line discovered during refueling shutdown.	Probably inadequate pipe hanger design. Piping was not designed to withstand transient loads. A spurious closure of MSIV may have generated enough load to distort the hanger.	Note 1. Design of the pipe support system components in main steam lines should include consideration of potential steam hammer dynamic loads.

Table 5-3 (Continued) WATER HAMMER EVENTS IN PWR MAIN STEAM SYSTEM

EVENT NO.	PLANT/ DESIGN	COM. OP. DATE	EVENT DATE	OPERATING MODE	WATER HAMMER TYPE	MECHANICAL FUNCTION	INITIAL INDICATION/ DAMAGE	CAUSE AND EVENT BASIS	COMMENTS
37	Zion-1 W	12/31/73	6/6/74	750 MWe	Water entrainment in turbine exhaust line.	Steam turbine driven auxiliary FW pump startup.	Water hammer noise. Pipe hanger damaged.	Inadequate exhaust piping design and/or poor maintenance procedure. Auxiliary FW pump steam driven turbine exhaust drain line had accumulated rain water and had too much back pressure.	Design of exhaust piping must be checked for possible back pressure buildup. Maintenance procedure should require regular cleaning of traps.
16	Indian Point-2 W	8/73	6/7/80	Hot Shutdown	Probably water hammer in SG blowdown line.	Unknown	Control room indication of secondary side leakage to containment atmosphere. Failure of a snubber pipe clamp, breakage of a spring hanger support rod, and a crack in the shell drain.	Inadequate pipe support design and/or warm-up procedure.	Note 1. Check pipe support design and adequacy of warm-up procedure for the SG blowdown line.
30	San Onofre-1 W	1/1/68	1/74	Unknown	Unknown (probably water hammer due to wave reflection)	Unidentified (probably valve closure)	Damaged knee supports and snubber. Knee supports on MS line, and a knee support and snubber on main FW line were damaged.	Cause unknown. Lateral loading neglected, anchor plate incorrectly installed, and bolts wrong size.	Note 1. Verification required to show that final designs are adequate.

NOTE 1: No water hammer was actually witnessed. The occurrence of a water hammer was reported based upon observed damage.

Table 5-4 WATER HAMMER EVENTS IN PWR RESIDUAL HEAT REMOVAL SYSTEM (RHRS)

EVENT NO.	PLANT/ DESIGN	COM.OP. DATE	EVENT DATE	OPERATING MODE	WATER HAMMER TYPE	MECHANICAL FUNCTION	INITIAL INDICATION/ DAMAGE	CAUSE AND EVENT BASIS	COMMENTS
25	Rancho Seco-1	4/17/75	12/15/78	Refueling Shutdown	Probable Flow into Voided Line	Pump Start	Damage found during inspection. Pipe supports and snubbers damaged.	Incorrect procedures. Incorrect valve lineup before pump start.	Note 1. Damage to both "A" and "B" decay heat systems piping supports.

NOTE 1: No water hammer was actually witnessed. The occurrence of a water hammer was reported based upon observed damage.

Table 5-5 WATER HAMMER EVENTS IN PWR ECCS SAFETY INJECTION SYSTEM

EVENT NO.	PLANT/ DESIGN	COM.OP. DATE	EVENT DATE	OPERATING MODE	WATER HAMMER TYPE	MECHANICAL FUNCTION	INITIAL INDICATION/ DAMAGE	CAUSE AND EVENT BASIS	COMMENTS
23	Palisade CE	12/31/71	5/14/74	Cold Shutdown	Flow-into-partially-voided line	Low pressure SI pump suction line valve opening	Pipe restraint pulled loose from mounting. Anchor bolts on pump suction line pipe restraint pulled out of mounting.	Poor operating procedure. Air was apparently introduced into the system during the testing and filling of the sodium hydroxide system.	Note 1. Applicable operating procedures should be reviewed to eliminate possibility of introducing air into line.
26	Robinson-2 W	3/7/71	12/19/78	Unknown	Flow-into-voided line	ECCS safety injection pump startup	Damage observed during 12/19/78 inspection. The water hammer resulted in six supports of the cold leg safety injection line being in a faulted condition (inoperable during certain design plant condition).	Inadequate design and/or procedures. The water hammer was postulated to have occurred during testing when flow was admitted into the voided injection line.	Note 1. Lines subject to voiding and abrupt flow surges should incorporate means to maintain the lines full of water at all times and/or procedures should specify venting.
29	San Onofre-1 W	1/1/68	10/21/73	Normal Operating	Flow-into-partially-voided line	Safety injection	Improper valve closure during testing after incident. Valve bolts and pipe hanger support failed.	Inadequate design and/or procedures. Safety injection line had an air bubble. Line design did not permit adequate on-line venting.	Note 1. Safety injection piping design should be evaluated for adequate venting. Procedures should specify frequent venting.
34	Surrey-2 W	5/1/73	1974	Startup (accumulator discharge line leak test)	Steam bubble collapse	Accumulator discharge valve opening	Damaged pipe restraint support. Pipe restraint support was damaged.	Poor operating procedure. Line pressure was reduced below saturation pressure during leak testing. Water hammer occurred when accumulator discharge valve was opened.	Note 1. Operating procedure during leak testing should be checked to ensure that line pressure is maintained at a level above the saturation pressure to prevent formation of steam voids in line.

NOTE 1: No water hammer was actually witnessed. The occurrence of a water hammer was reported based upon observed damage.

Table 5-6 WATER HAMMER EVENTS IN PWR CHEMICAL AND VOLUME CONTROL SYSTEM

NOTE 2: Event may not have been caused by water hammer but rather by vibration induced by improperly installed valve component.

EVENT NO.	PLANT/ DESIGN	COM.OP. DATE	EVENT DATE	OPERATING MODE	WATER HAMMER TYPE	MECHANICAL FUNCTION	INITIAL INDICATION/ DAMAGE	CAUSE AND EVENT BASIS	COMMENTS
19	Maine Yankee CE	12/28/72	6/2/77	Low Power Test	Possible flow into-voided-line and/or steam bubble collapse	Letdown pressure control valve instability	Fluctuation in letdown flow rate. Valve positioner bolts worked loose. Associated air line was severed. Drain line and pressure tap on letdown line were broken.	Loose valve positioner severed the air supply line. Loss of air signal to valve controller caused flow oscillations. Resulting letdown line movement broke the body drain line and the pressure tap line.	Note 1 Note 2
27	Salem-1 W	6/30/77	1/3/77	Hot Shutdown	Possible steam bubble collapse or line vibration	Unavailable	Leak detection system alarmed. 3/4" vent line break.	Excessive vibration caused the 3/4" vent line to shear downstream of the joint to the main letdown line.	Note 1 Note 2

NOTE 1: No water hammer was actually witnessed. The occurrence of a water hammer was reported based upon observed damage.

NOTE 2: There are no safety-related effects resulting from malfunctions in these systems. Implementation of recommendations listed in comments should be based upon plant unavailability rather than nuclear safety considerations.

Table 5-7 WATER HAMMER EVENTS IN PWR CONDENSER SYSTEM

EVENT NO.	PLANT/ DESIGN	COM. OP. DATE	EVENT DATE	OPERATING MODE	WATER HAMMER TYPE	MECHANICAL FUNCTION	INITIAL INDICATION/ DAMAGE	CAUSE AND EVENT BASIS	COMMENTS (NOTE 2)
2	Arkansas-1 B&W	12/19/74	3/75	Unknown	No indication of water hammer	Unidentified (probably turbine bypass valve opening)	Condenser damage noted during routine inspection. Failed turbine bypass spargers, impingement plates on turbine-to-condenser expansion joint, and tie rods and expansion joints.	Unidentified. (Probably inadequate design of turbine bypass spargers and several components inside the condenser). Anticipated turbine bypass transient flow.	No indication of water hammer. Problem appears to be inadequate design of turbine bypass spargers and several components inside the condenser.
4	Beaver Valley-1 W	4/30/77	7/76	10% Power	Hydraulic transient	Heater drain tank high level dump valve opening	Condenser tube leak. First of two events (see Event 5). Broken flow deflector and condenser tubes.	Inadequate design of deflector plate. Water piston effect from heater drain tank high level dump valve on the flow deflector plate in the condenser.	Check design of flow deflector plate in the condenser.
5	Beaver Valley-1 W	4/30/77	10/76	30% Power	Hydraulic transient	Heater drain tank high level dump valve opening	Condenser tube leak. Second of two events (see Event 4). Broken flow deflector and condenser tubes.	See Event 4.	See Event 4.
14	Indian Point-1 W	1962-63	1970	Unknown	Unknown (Probably due to wave reflection)	Unidentified (Probably main condensate deaerator level regulating valve malfunction)	Not identified. (Probably water hammer noise). Cracks in condensate piping and regulating valve damage.	Either inadequate design or poor quality control. Valves malfunctioned, causing severe water hammer in main condensate system. Probably too rapid closing due to misplaced valve positioners.	Note 1. Select level regulating valves that have durable components and good performance characteristics. Design piping arrangement that will eliminate potential water hammer. Test valve and controller performance. Inpsect valve and controller for damage.

NOTE 1: No water hammer was actually witnessed. The occurrence of a water hammer was reported based upon observed damage.

Table 5-8 WATER HAMMER EVENTS IN PWR COOLING WATER SYSTEM

EVENT NO.	PLANT/ DESIGN	COM.OP. DATE	EVENT DATE	OPERATING MODE	WATER HAMMER TYPE	MECHANICAL FUNCTION	INITIAL INDICATION/ DAMAGE	CAUSE AND EVENT BASIS	COMMENTS
9	Beaver Valley-1 W	4/30/77	7/1/80	0% Power	Possible flow-into-voided-line	Pump startup	Damage observed during routine inspection. Bowing of embedment plate and spalling of the surrounding concrete in a few locations.	Procedural deficiency. Component cooling water flow to RHR heat exchangers was not throttled and flow surged into a partially voided line.	Note 1
20	Millstone-2 CE	12/26/75	7/22/75	Construction Phase	Possible flow-into-voided-line	Valve Opening/ Closure	Water hammer on startup and shut down of diesel generator. Inlet nozzle to diesel generator air cooler water box over-stressed and fractured.	Inadequate design. Outlet control valve arrangement on service water line to air cooler initiated hydraulic transient.	
28	San Onofre-1 W	1/1/68	10/9/69	Power Operation	Unknown (water hammer due to wave reflection)	Valve Closing	Intake gate was cracked, deformed, and torn loose from guide slots. Hydraulic actuator was damaged.	Inadequate design/quality control. Epoxy bonding material between reinforced concrete gate slabs and stubs holding the slabs to the actuator was misapplied. Gate dropped into intake line flow path.	This event does not appear to be water hammer.

6.0 IMPLEMENTATION OF PREVENTIVE MEASURES

This section discusses recommendations to prevent or mitigate water hammer and potential means for their implementation.

6.1 Means of Implementation

6.1.1 Plants in Design or Construction

It is recommended that a Standard Review Plan (SRP) or Branch Technical Position (BTP) be issued on water hammer. The SRP or BTP should be generic in nature and address the recommendations contained in section 6.2. Existing SRPs for the affected systems should be revised to refer to the generic SRP or BTP.

6.1.2 Operating Plants

It is recommended that a generic letter be issued to operating plants listing the recommendations contained in section 6.2.

6.2 Recommended Measures for the Prevention or Mitigation of Water Hammer in Light Water Reactor Plants

a. Operator Training

It is recommended that plant operators, including personnel responsible for writing maintenance instructions and supervising maintenance activities, receive training on the causes and prevention of water hammer.

b. Operating and Maintenance Procedures

It is recommended that the applicant review all operating maintenance and testing procedures for the systems listed below for their appropriateness in preventing water hammer.

- BWR systems
  - Residual heat removal
  - High-pressure coolant injection
  - Core spray
  - Essential service and cooling water
  - Isolation condenser
  - Feedwater
  - Main steam

- PWR systems
  - Emergency core cooling (safety injection)
  - Feedwater
  - Main steam
  - Essential service and cooling water

c. Void Detection

It is recommended that void detection and alarm provisions be installed in for the systems listed below. Void detection should be provided at all points in the normally liquid-filled lines where voids or steam bubbles could form or collect. When voids are present the system should be considered inoperable with respect to technical specification requirements, but available for emergency use. The voids should be filled and vented immediately. It is difficult to quantify an acceptable void size. Therefore, it is desirable that the void detection system be able to detect the incipience of voiding. Such a system would permit the correction of voids before they reach a significant size. The presence of a large void should be considered a reportable item. It should be shown that all potential void points have been monitored. Open-loop service water systems may be considered operable if analysis has been performed to demonstrate that there will be no adverse effects if the system is started with voids present.

- BWR systems
    - Residual heat removal
    - Core spray
    - High-pressure coolant injection
    - Essential service water

- PWR systems
    - Emergency core cooling
    - Essential service water

d. Keep-Full Syst

It is recommended that continuously operating keep-full systems be used for filling voids in normally water-filled lines in the systems listed below. A jockey pump or a storage tank at a higher elevation then the lines of concern may be considered to be an adequate keep-full system.

- BWR systems
    - Core spray
    - High-pressure coolant injection
    - Reactor core isolation cooling
    - Residual heat removal

e. Filling Safety-Related, Open-Loop Service Water Systems

It is recommended that one of the following criteria be demonstrated for open-loop service water systems:

1. Voids can be filled within the required start time through a manually initiated fill system. This provision is applicable to manually started systems only.

2. Neither column separation nor voiding can occur during standby or following pump shutdown.

3. The system is designed with a startup mode that slowly fills and vents the discharge lines in such a manner as to prevent water hammer on pump start up.

4. The system is designed to maintain function following a postulated water hammer event.

f. Venting

It is recommended that venting provisions be installed on the systems listed below. Venting should be provided at all points in the normal lines where voids or steam bubbles could form or collect. It should be demonstrated that all potential void points can be vented. The vent system should either be automatic, remotely actuated, or should be designed for ease of operator usage.

- BWR systems
  - Residual heat removal
  - Core spray
  - High-pressure coolant injection
  - Essential cooling water
  - Reactor core isolation cooling

- PWR systems
  - Emergency core cooling
  - Essential cooling water

g. Turbine Exhaust Line Vacuum Breakers

It is recommended that vacuum breakers be provided in the turbine exhaust lines that have a liquid interface. This provision is only applicable for safety-related systems. The design should not violate the containment isolation boundary.

Applicable Systems:

- BWR systems
  - High-pressure coolant injection
  - Reactor core isolation cooling

h. HPCI Steam Line Drain Pot

It is recommended that:

1. The adequacy of the sizing of the HPCI drain pot system be demonstrated.

2. The level indicators on the HPCI drain pot system be checked for operability periodically and repaired if necessary.

i. HPCI Turbine Inlet Line Isolation Valves

It is recommended that the technical specifications prohibit opening the inboard isolation valve unless the outboard isolation valve is fully open. They should also prohibit closing the outboard valve unless the inboard valve is fully closed. These provisions should apply for all operating conditions except cold shutdown. Neither valve should contain a seal-in feature on opening. The inboard valve design and its operating procedures should permit gradual line warm up.

j. Feedwater Control Valve

It is recommended that the feedwater control valve supplier verify that the valve design parameters including actuator, flow coefficient (CV), and trim are compatible with all final designed operating conditions of the condensate and feedwater system. Furthermore, the valve and its control system should be designed to minimize the potential for instability, vibrations, and water hammer.

Design features that minimize instability include balanced trim designed for all pressure drop and flow configurations, stiff actuators, moderate rate of operator response, long valve strokes and minimal pressure drop compatible with achieving proper control.

k. Steam Hammer and Relief Valve Discharge

It is recommended that:

1. The design bases for the operability and support of main steam systems consider steam hammer resulting from the most rapid anticipated closure of all system valves including the turbine stop valves.

2. The design basis for the operability and support of the systems listed below consider fluid forces resulting from safety and relief valve operation.

   o BWR systems
      - Main steam

   o PWR systems
      - Main steam
      - Reactor coolant system pressurizer.

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This document presents the results of an evaluation of water hammer events in LWR power plants. The evaluation was based upon reports of actual events, typical plant design drawings and operation procedures. Included in this report are design and operating recommendations for the prevention or mitigation of water hammer occurrence.

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