NUREG-0927
Revision 1

Evaluation of Water Hammer Occurrence in Nuclear Power Plants

Technical Findings Relevant to Unresolved Safety Issue A-1

U.S. Nuclear Regulatory Commission

Office of Nuclear Reactor Regulation

A. W. Serkiz, Task Manager

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A. W. Serkiz, Task Manager

Division of Safety Technology
Office of Nuclear Reactor Regulation
U.S. Nuclear Regulatory Commission
Washington, D.C. 20555

ABSTRACT

This report, which includes responses to public comments, summarizes key technical findings relevant to the Unresolved Safety Issue A-1, Water Hammer. These findings were derived from studies of reported water hammer occurrences and underlying causes and provide key insights into means to minimize or eliminate further water hammer occurrences. It should also be noted that this report does not represent a substitute for current rules and regulations.

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ACKNOWLEDGEMENTS

The technical findings relevant to the Unresolved Safety Issue A-1, Water Hammer, which are set forth in this report, represent the combined efforts of staff at the Nuclear Regulatory Commission, EG&G - Idaho, Inc., and Quadrex Corporation. The following persons deserve special mention for their participation and contributions:

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NOMENCLATURE

Acronyms

AE	Architect/Engineer
AFW	Auxiliary Feedwater
ALARA	As Low as Reasonably Achievable
ANSI	American National Standard Institute
ASB	Auxiliary Systems Branch
ASME	American Society of Mechanical Engineers
B&PV	Boiler and Pressure Vessel
BTP	Branch Technical Position
B&W	Babcock and Wilcox
BWR	Boiling Water Reactor
CE	Combustion Engineering
CRD	Control Rod Drive
CV	Valve Flow Coefficient
CVCS	Chemical and Volume Control System
ECCS	Emergency Core Cooling System
FCV	Feedwater (or Flow) Control Valve
HHSI	High Head Safety Injection
HPCI	High-Pressure Coolant Injection
LOCA	Loss-of-Coolant Accident
LPCI	Low-Pressure Coolant Injection
LWR	Light Water Reactor
NRC	Nuclear Regulatory Commission
NSSS	Nuclear Steam Supply System
NUREG	Nuclear Regulation
PHSG	Preheat Steam Generator
PWR	Pressurized Water Reactor
RCIC	Reactor Core Isolation Cooling
RCS	Reactor Coolant System
RHR	Residual Heat Removal
RWCU	Reactor Water Cleanup
SGWH	Steam Generator Water Hammer
SRP	Standard Review Plan
SRV	Safety/Relief Valve
TAP	Task Action Plan
TSV	Turbine Stop Valve
USI	Unresolved Safety Issue

EXECUTIVE SUMMARY

This report presents the NRC staff's technical findings regarding the Unresolved Safety Issue (USI) A-1, Water Hammer, and presents the results of the concluding evaluations associated with resolving this safety issue and includes responses to public comments. The major findings can be summarized as follows:

1. Total elimination of water hammer occurrence is not feasible, due to the possible coexistence of steam, water, and voids in various nuclear plant systems. Experience shows that design inadequacies and operator- or maintenance-related actions have contributed about equally to initiating water hammer occurrences.

2. Since 1969, approximately 150 water hammer events have been reported through the NRC's Licensee Event Reports (LERs). Damage has been principally limited to pipe support systems. Approximately half of these events have occurred either in the pre-operational phase or the first year of commercial operation. This suggests a learning period exists in which design deficiencies are corrected and operating errors are reduced.

3. Water hammer frequency peaked in the mid-1970s, at a time when the rate of introducing new plants into commercial operation was the highest. Experience led to corrective design changes (e.g., use of J-tubes to eliminate steam generator water hammer and "keep-full" systems, vacuum breakers, etc.) which reduced the frequency of occurrence.

4. Steam generator water hammer (SGWH) associated with top feedring SGs appears to have been corrected by the use of design features.

and the test requirements specified in the NRC's Branch Technical Position ASB 10-2, "Design Guidelines for Water Hammers in Steam Generators with Top Feedring Designs."

The major conclusions reached are that the frequency and severity of water hammer occurrence can be and to some extent have been significantly reduced through design features such as keep-full systems, vacuum breakers, J-tubes, void detection systems and improved venting procedures, proper design of feedwater valves and control systems and increased operator awareness and training; and that the current potential for significant damage as a result of water hammer events is less than it was in the early and mid 1970's.

Total elimination of water (steam) hammers is not feasible, due to various inherent features of plant design and operation. Therefore, currently accepted design practices for including anticipated water (steam) hammers as occasional mechanical loads in the design basis of piping and their supports systems should be maintained.

These topics are discussed in more detail in the report which follows.

Although publication of this technical findings report and of associated revisions to the Standard Review Plan complete the staff's work under the Task Action Plan for USI A-1, and constitute technical resolution of the issue as defined therein, the potential for water hammer loads remains an important consideration in the design and operation of nuclear power plants. The staff recognizes the continuing importance of ongoing activities aimed at further reductions in the frequency and possible magnitude of water hammer events and consideration of water hammer effects in nuclear power plant design. These include the activities of the NRC Piping Review Committee, which is currently reviewing regulatory practices related to Pipe Cracks, Pipe Breaks, Seismic Design and Dynamic Load/Load Combinations. Water hammer loads are one of several dynamic loads which will be reviewed with respect to experience and current design practices. These activities are integrated with similar activities under the PVRC Technical Committee on Piping where the aim is to improve piping design with respect to dynamic loads. Finally, there are foreign programs aimed at correlating water hammer energy, with damage to piping systems. The joint efforts of these activities should continue.

1.0 INTRODUCTION

This report presents the results of concluding technical evaluations relevant to Unresolved Safety Issue (USI) A-1 Water Hammer, the safety significance of this issue as currently viewed, and potential methods to minimize the frequency and severity of water hammer occurrences.

Water hammer, as discussed in this report, encompasses more than the classical case in which pressure waves, caused by the sudden interruption of flow, are reflected through liquid-filled lines. Water hammers in nuclear power plants have been caused by voiding in normally water-filled lines, steam condensation in lines containing both steam and water, and the entrainment of water in steam-filled lines, as well as by rapid valve action, the classical cause. These underlying causes, the systems they affect, and means for their prevention or mitigation are discussed.

1.1 Safety Significance and Background

The safety significance of a water hammer in a particular system is related to the level of damage incurred (water hammer can introduce large hydraulic loads), the frequency of event occurrence and the safety function of the system.

During the early 1970s the number of water hammer events reported increased. This increase coincided with the increase in the number of plants starting up, as shown in figures 1-1 and 1-2. The staff's concern also increased and were set forth in NUREG-0582 (reference 1). As a result, water hammer was designated an Unresolved Safety Issue (USI) in late 1978.

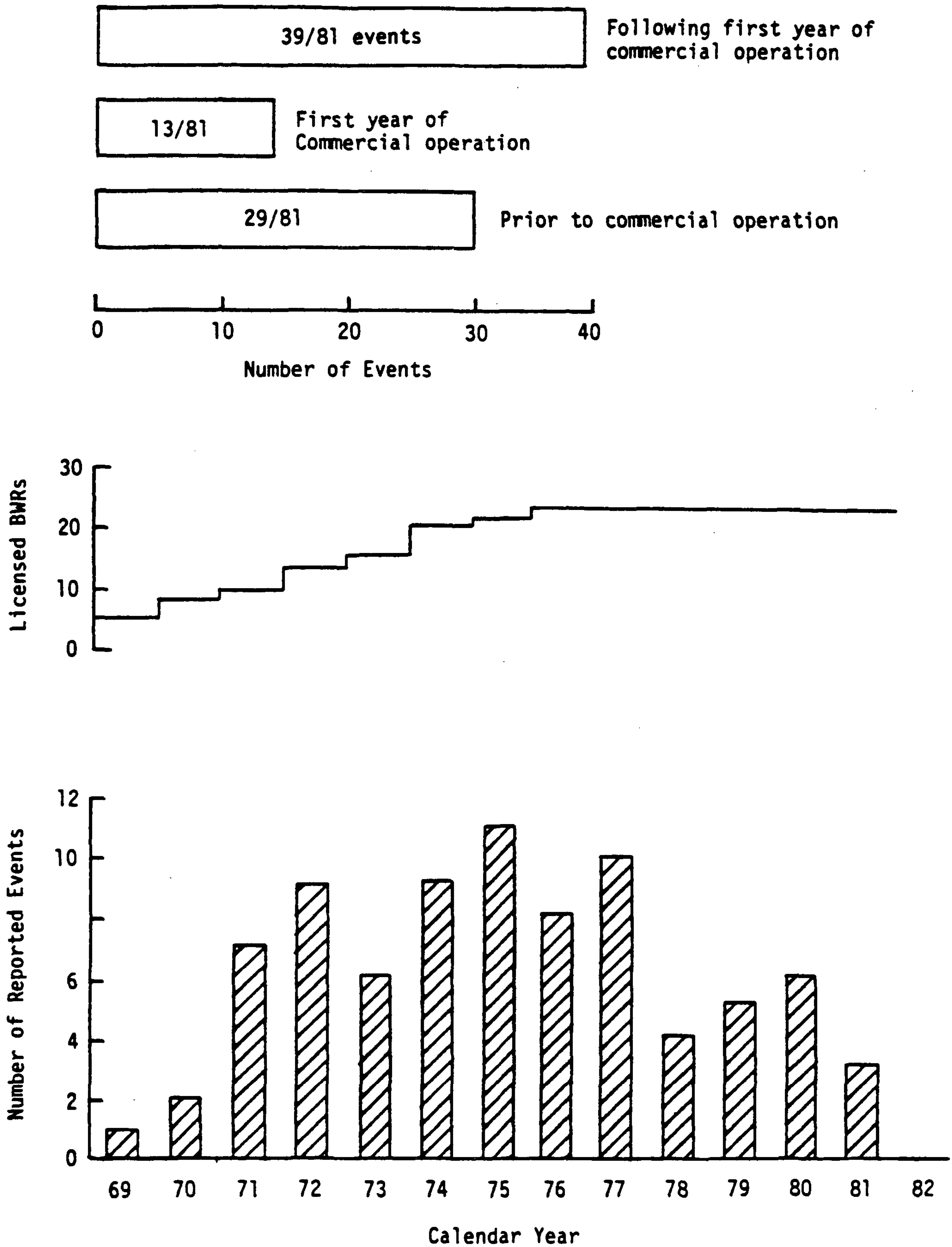


Figure 1-1 Reported Water hammer occurrences in US BWRs.

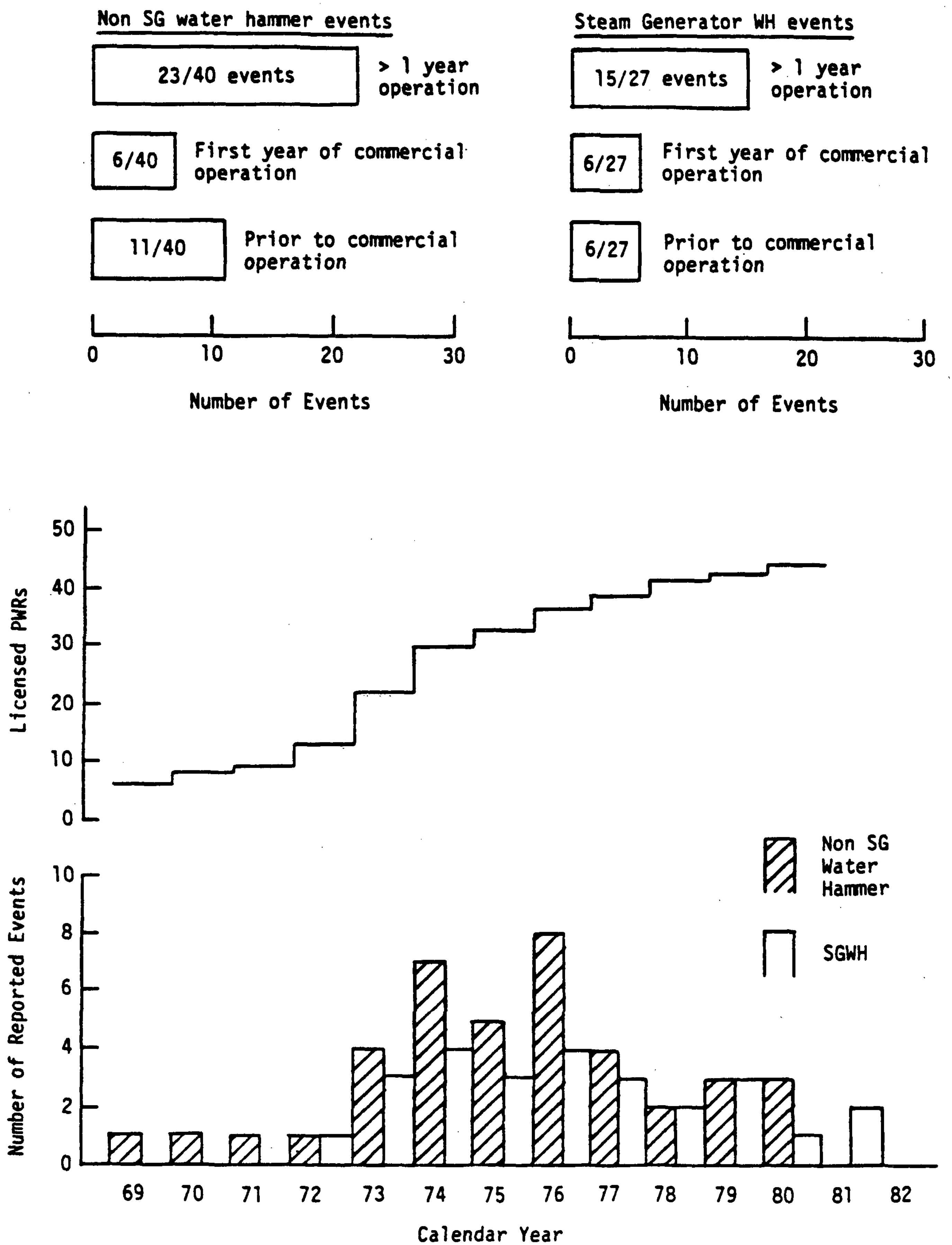


Figure 1-2 Reported water hammer occurrences in US PWRs.

Although much of the water hammer damage was limited to piping support systems, steam generator water hammer frequency increased sharply from 1973 to 1976 and was highlighted by the feedwater line crack occuring at Indian Point 2 in late 1973. An evaluation of PWR steam generator water hammer causes was undertaken in 1976, and the results are reported in NUREG-0291 (reference 2). Recommended design modifications to prevent or mitigate SGWH were embodied in the NRC's Branch Technical Position (BTP) ASB 10-2, "Design Guidelines for Water Hammers in Top Feedring Design," attached to Standard Review Plan (SRP) section 10.4.7 (reference 3).

In addition, efforts were undertaken to analyze water hammers and attempt to predict their occurrence and magnitude (references 4, 5, 6, and 7). Although underlying causes had been identified for sometime (reference 1), the analytical attempts were not successful due to computer code limitations in modeling actual physical phenomena (e.g., steam void collapse), modeling complexity of the interconnected subsystems, and the very large number of system alignments possible under various plant operating conditions. Simply stated, analysis could not provide adeqate information to eliminate water hammer.

Therefore, evaluations of reported occurrences were undertaken to carefully review levels of damage, underlying causes, frequency of occurrence, and system design or operational implications. A compilation of known or suspected water hammer events in nuclear power plants from 1969 to 1981 is contained in reference 8.

1.2 Current Safety Picture

The severity and frequency of reported water hammer events (reference 8) and evaluations of the damage and safety implications (reference 9) indicate that water hammer is not as significant a safety issue as previously thought for the following reasons:

a. The damage for most of the reported water hammer events has been limited to piping and equipment supports.

b. Many of the reported events were either not water hammers, or occurred in nonsafety systems. None of the water hammer events placed a plant in a faulted or emergency condition. None of the water hammer events resulted in a radioactive release.

c. About half the approximately 150 reported water hammer events since 1969 have occurred during preoperational testing and the first year of commercial operation (see figures 1-1 and 1-2). This suggests a learning process and increased operator awareness of the potential for water hammers.

d. Water hammer frequency has decreased. The frequency of water hammer events peaked during the mid-1970s. Experience has brought about design and operational modifications which have reduced the frequency and the potential severity of water hammer in many systems. Two examples are: a) the use of J-tubes in top feedring steam generators to increase drain time, thereby reducing the potential for steam collapse water hammer, and b) the use of jockey pumps in BWR keep-full systems to prevent pump startup into voided lines.

1.3 Key Findings

The key findings, upon which the recommended technical resolution of USI A-1 is based, are as follows:

a. Water hammers continue to occur, but at a low frequency. Total elimination of water hammer is not feasible due to design and operational conditions wherein steam, water, and voids can coexist within a system(s).

b. The overall incidence of water hammer in nuclear power plants has declined considerably in recent years. The decline in the incidence of water hammer events is due to the implementation of various design and operational modifications.

c. The most common cause of water hammer events is line voiding. Other significant causes include steam condensation, feedwater control valve instability, and steam water interfaces. Although these are the generic causes, many of the events have resulted from both design and operational deficiencies. Tables 1-1 and 1-2 summarize water hammer events in PWR and BWR systems, along with attendant safety significance and underlying causes.

d. BWRs continue to report a higher frequency of events than PWRs, primarily because of two factors. The first factor is the susceptibility of BWR ECCS lines to leakage-caused voiding because of the low elevation of the suppression pool which is the ECCS water source. The other factor is the presence of steam-water interfaces in BWRs.

e. Following the implementation of design features and testing contained in BTP ASB 10-2 (reference 3), the frequency of steam generator water hammer in top feedring design steam generators has been essentially eliminated. Additional review of water hammer potential for bottom feed (preheat) steam generators is in process.

f. The frequency and severity of water hammers can be significantly reduced through proper design features, such as keep-full systems, improved venting, void detection, feedwater control valve design verification and vacuum breakers.

g. The frequency and severity of water hammers can be significantly reduced by operator awareness and training, and by improving plant operating and maintenance procedures that cover features such as line warmup, proper valve usage, venting and draining, and void correction.

h. State-of-the-art mechanistic or quantitative two-phase analysis of water hammer phenomena is not a practical means of resolving all water hammer. Although, there are many water hammer events that can be analyzed, the extensiveness of possible plant conditions, alignments, and computer code calculational limits preclude analyzing all possible scenarios.

i. Anticipated water (steam) hammer events, caused by components performing in their intended manner should be included as occasional loads in the design basis of piping and their support systems.

1.4 Report Organization

Section 2.0 provides a more comprehensive technical discussion of reported events, underlying causes, and systems affected. Section 3.0 summarizes key technical findings and provides additional details on measures to prevent or mitigate water hammers.

TABLE 1-1. Overview of Reported PWR Water Hammer Events

System	Number of Events	Safety Significance*	Underlying Causes
Feedwater	13	Moderate	Control valve instabilities
ECCS Safety Injection	4	Moderate	Voided lines (3) Steam bubble collapse (1)
Reactor Primary System	5	Moderate	Relief valve discharge
Cooling Water	3	Moderate	Voided lines (2)
Steam Generators	27	High	Top feedring drainage followed by steam bubble collapse
Main Steam	8	Low	Valve closures/openings (4) Steam-water entrainment (3) Relief valve discharge (1)
Residual Heat Removal	1	Low	Incorrect valve alignment causing voided line
Chemical and Volume Control	2	Low	Voided line, steam bubble collapse
Condenser	4	Low	Design and procedures
TOTAL	67		

*Safety significance as used here is a relative rating based on severity of damage reported, frequence of occurrence, and the role of the particular system involved. These ratings are only relative to water hammer in the other systems listed below. The ratings are not the result of probabilistic risk assessments (PRA) and are not ratings of risk to plant personnel or the public.

TABLE 1-2. Overview of Reported BWR Water Hammer Events

System	Number of Events	Safety Significance*	Underlying Causes
Core Spray	9	High	Voided lines
Residual Heat Removal:			
Shutdown Cooling	7	High	
Reactor Vessel Heat Spray	1	Low	Voided lines (11), steam
Containment Spray	4	Moderate	bubble collapse (8), steam
Low-Pressure Coolant Injection	1	Low	water entrainment (1), unknown (3)
Fuel Pool Cooling	3	Low	
Steam Condensing	7	Moderate	
High-Pressure Coolant Injection	20	High	Steam water entrainment (12), steam bubble collapse (4), voided lines (3)
Cooling Water	9	High	Voided lines (5), design and procedures (2), water column separation (2)
Main Steam	6	Moderate	Steam water entrainment (2) Valve operation (4)
Isolation Condenser	4	Moderate	Steam water entrainment
Feedwater	3	Low	Valve controller instabilities
Condenser	3	Low	Maintenance and design errors
Reactor Core Isolation Cooling	2	Low	Steam water entrainment (1)
Reactor Water Cleanup	1	Low	Unknown
Plant Process Steam	1	Low	Steam bubble collapse
TOTAL	81		

*Safety significance as used here is a relative rating based on severity of damage reported, frequence of occurrence, and the role of the particular system involved. These ratings are only relative to water hammer in the other systems listed above. The ratings are not the results of probabilistic risk assessments (PRA) and are not ratings of risk to plant personnel or the public.

2.0 TECHNICAL DISCUSSION

2.1 Background and Technical Approach

2.1.1 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 rapid 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). Water hammer types are discussed in section 2.1.2.

b. Anticipated Water (Steam) 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 (Steam) 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. Nonwater (Non-Steam Hammer) Hammer Hydraulic Transients. Hydraulic transients that do not conform to definition a. above are not considered to be water hammers. Examples of nonwater (steam) hammer transients are steady-state pipe vibrations or oscillations, normal pressure transients and pump instabilities.

2.1.2 Water Hammer Types

The water hammers encountered in nuclear power plants emcompass more than the classical case in which pressure waves, caused by the sudden interruption of flow, are reflected through liquid-filled lines. The majority of water hammers occurring in power plants have been caused by the entrainment of water in normally steam-filled lines, steam and water flow in the same line, and voiding in normally water-filled lines.

Water entrained in steam lines causes water hammers when the water slugs are stopped suddenly by obstructions such as closed valves. Further discussion of water entrainment is contained in section 2.4.4.

The presence of nonequilibrium steam and water flow in the same line can cause local steam condensation followed by large pressure drops and rapid slug acceleration. Water hammer forces are generated when the slugs impact a water column or other obstacle. Sections 2.4.2 and 2.4.5 contain detailed discussions of steam bubble collapse phenomena.

Voids can occur in normally water-filled lines for a variety of reasons. When water is pumped into the voided line, the water column accelerates through the void. When the column is suddenly stopped upon impact with an obstacle such as a valve or water column, water hammer forces are generated. A more detailed discussion of voiding is provided in section 2.4.1.

2.1.3 History of Evaluation

Because of the continuing incidence of water hammer events, the variety of phenomena, and the potential safety significance of the systems involved, water hammer was classified as USI A-1, and task action plan TAP A-1 was developed to provide a plan for resolving

USI A-1. However, even prior to the classification of water hammer as a USI, efforts were in process to prevent or mitigate water hammer.

NUREG-0291 (reference 2) presented the results of a study of the cause and effects of past PWR steam generator water hammer (SGWH) events. Recommendations were developed to prevent or mitigate SGWH.

In 1977 letters were issued to certain PWR licensees requiring submission of proposed plant design or procedural modifications to prevent damaging water hammers in the steam generators. Reviews of the licensee responses were made under the generic review program, "Steam Generator Feedwater Flow Instability."

Operating PWR plants having certain feedwater flow control valves were reviewed with respect to actions already taken or still needed to prevent damaging water hammer.

Following the classification of water hammer as a USI, NUREG-0582 (reference 1) was issued. NUREG-0582 was the first overall summary evaluation of water hammer in nuclear power plants. The staff reviewed information on water hammer events obtained primarily from licensee event reports and information requests to licensees. The staff concluded that continued plant operation and licensing was warranted, pending the evaluation of the water hammer issue, as outlined in TAP A-1. However, concurrently, the staff concluded that the overall frequency of water hammer events was unnecessarily large and that corrective steps in design and in plant operation should continue to be pursued through the licensing review process.

Numerous analytical studies were undertaken to analyze various water hammer phenomena. The phenomena analyzed included filling of voided systems (reference 4), fluid transient forcing functions for piping systems (reference 5), steam void collapse (reference 6), and check valve fluid transients (reference 7). The studies were undertaken to determine the limitations and the present state of existing computer codes. Table 2-1 presents the key findings of these studies, including code limitations and recommendations for experimental verification of analytical results.

Because of the analytical limitations, it was concluded that further development of analytical tools was not a feasible solution to the water hammer issue. As an example, even the advanced codes did not hold promise for calculating steam-water condensation phenomena, which would be required for analyzing steam void collapse, which is followed by water slug propagation and impact loads. It was also recognized that the potential combinations of system alignments and plant conditions conducive to water hammer were far toonumerous to permit analysis of all potential water hammer scenarios.

Rather than continue analytical studies, emphasis was placed on evauation of events and plant design and operation to prevent or mitigate water hammer. The evaluations, discussed below, represent the major basis for the resolution of the water hammer safety issue.

NUREG-0291, discussed previously, was the basis for the initial evaluation of steam generator water hammers (SGWH). NUREG-0918 (reference 10) presents the plans for the prevention or mitigation of SGWH. NUREG-0291 summarizes causes of SGWH, various design and operating changes employed to prevent or mitigate SGWH, and implementation and status of modifications at each operating PWR plant.

TABLE 2-1

Water Hammer Analytical Studies

Study Ojective	Key Findings
Analyze rapid filling of voided piping systems (BWR core spray line-filling using SOLA-PLOOP computer code,) (reference 4)	1. Modified SOLA-PLOOP hydrodynamics code applicable. 2. Experimental verification of analytical tool recommended.
Formulate analytical procedure to predict structural sequences of fluid transients in nuclear piping systems, (reference 5)	1. Analytical procedure developed for: a. Sudden check valve closure of a BWR primary feedwater line, b. Simulated BWR core spray line experiencing an instantaneous valve opening. 2. Significant potential loads on piping systems.
Investigate steam-void-collapse water hammer initiating mechanisms, (reference 6)	1. K-FIX/MOD1 code judged inadequate due to to treatment of interphase heat transfer and mass transfer. 2. Analysis of experimental data with advanced codes like TRAC or THERMIT advised.
Construct analysis tool for analyzing fluid transients in piping systems having a check valve, (reference 7)	1. RELAP5 adaptable to model check valve, and perform BWR feedwater line transient calculations.. 2. Future experimental verification desirable.

NUREG/CR-1606 (reference 11) documents work performed to evaluate condensation-induced water hammer in preheat steam generators. NUREG/ CR-1606 concluded that condensation-induced water hammers could occur in preheat steam generators and recommended each plant be reviewed separately and that appropriate preoperational testing be performed. Such testing is currently being implemented through the Operating License review process.

NUREG/CR-3090 (reference 16) evaluates the potential for water hammer occurrence during AFW operation of preheat steam generators (PHSG). The evaluation concludes that the likelihood of water hammer occurrence during PHSG AFW operation was extremely low. Furthermore, if an event did occur, it should have no adverse effects on AFW system operation or plant safety.

NUREG/CR-2059 (reference 8) presents a compilation of data for reported water hammer events occurring from January 1, 1969, through May 1, 1981. The compilation was performed to facilitate an understanding of the frequency and severity of damage from and the underlying causes of water hammer. For each reported event, available information concerning underlying causes, damage incurred, plant operating conditions and corrective actions taken were presented. NUREG/CR-2059 also provided cross compilations to permit statistical evaluations concerning plant state (e.g., preoperational, first year, or after the first of operation) when the occurrences took place, the systems affected, reactor type and water hammer types. The information presented in NUREG/CR-2059 was the data base used for the systems evaluations reported in NUREG/CR-2781 and for developing most of the findings presented in this report.

NUREG/CR-2781 (reference 9) presents the results of an evaluation of water hammer events in LWR power plants. The evaluation was based upon the data of reference 8, typical plant design drawings and operating procedures. The evaluation identified the susceptibility of plant systems to water hammer and the safety significance of water hammer in plant systems. Generic causes of water hammer were also identified.

Included in NUREG/CR-2781 are design and operating recommendations for the prevention or mitigation of water hammmer occurrence. Most of the findings of NUREG/CR-2781 are incorporated in this report.

2.2 Frequency and Severity of Water Hammer Events

No water hammer incidents have resulted in the loss of containment integrity or the release of radioactivity outside of the plant. The frequency and severity of events in PWR systems are low, with the exception of SGWH and feedwater-control-valve-induced water hammers. The most serious BWR water hammer concern is line voiding.

Water hammer frequency increased as the number of operational reactors increased. Figures 1-1 and 1-2 show the number of reported events and licensed reactors for BWRs and PWRs. This data base shows that approximately half the events occurred during preoperational testing or the first year of commercial operation. On the other hand, not all of the operating plants have reported water hammer. Reference 8 provides water hammer event summaries for reported occurrences from 1969 through mid-1981.

For ease of presentation the discussions contained in this section are divided into three groups, based upon the plants or systems in which they occur. These groups are:

- o PWR steam generator water hammers (SGWH)
- o PWR non-SGWH water hammers
- o BWR water hammers.

2.2.1 PWR SGWH

Thirteen plants reported 27 PWR steam generator events (reference 8). No water hammer event damaged the integrity of the reactor coolant boundary. No water hammer incidents resulted in the loss of containment integrity nor release of radioactivity outside of the plant. In most of the events, damage was nonexistent or limited to the piping support system. Many reported events actually represented a series of several events recorded during a single, short time span at the same plant. Many events were not observed at the time of occurrence, but the damage observed indicated that these events were caused by SGWH. SGWH events have varied greatly in magnitude and consequences. Effects reported have ranged from minor noises and feedwater piping vibration to major feedwater support damage and one feedwater piping through-the-wall crack.

SGWH has occurred in steam generators with top discharge feedring designs. Branch Technical Position ASB 10-2 has been issued by the NRC to complement the corrective and preventive measures for new plants. Safety evaluations of corrective measures were issued for operating Westinghouse and Combustion Engineering-designed systems. SGWH has been essentially eliminated in plants conforming to the measures contained in BTP ASB 10.2 (reference 3).

2.2.2 PWR Non-SGWH

Forty PWR non-steam generator water hammer events were reported in NUREG/CR-2059. None had any adverse safety effect on a plant. No water hammer event rendered a safety system inoperable or damaged the integrity of the reactor coolant boundary. No water hammer incidents resulted in the loss of containment integrity nor release of radioactivity outside of the plant. In most of the events, damage was limited to the piping support system. The frequency and severity of water hammer events, having the potential to affect safety systems, in PWR plants has been low, with the exception of steam generator water hammers, which are previously discussed, and feedwater-control-valve-induced water hammers.

Eleven (28%) of the events occurred prior to the plant's commercial operation date, at seven different plants.

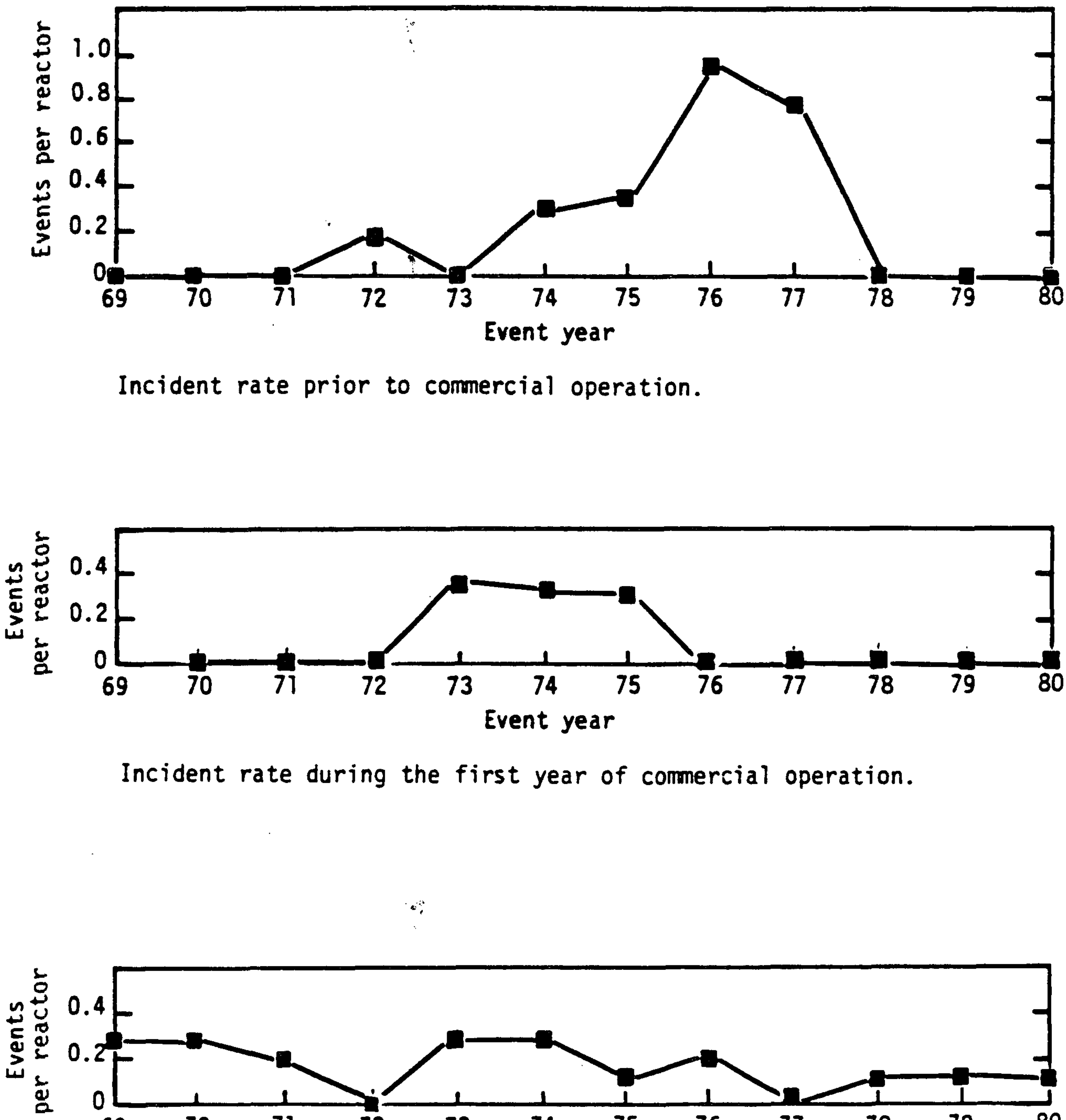
Six (15%) of the events occurred within one year after the plant's commercial operation date, at six different plants.

Twenty-three (58%) of the events occurred after the first year of plant's commercial operation, at 16 different plants.

The incident rates (events per year per reactor) for events which occurred after the first year of a plant's commercial operation are lower than the rates of events which occurred prior to that time (see figure 2-1). The average incident rate for all plants after the first year of commercial operation is 0.09 events per year per reactor.

This data illustrates that there is a learning curve in which operational and design deficiencies are corrected. However, water hammers will continue to occur at a relatively low frequency.

Of the 40 reported PWR non-steam generator events, NUREG/CR-2781 considered only 24 to be unanticipated water hammer events having the potential to affect safety systems. The other 16 events were either not water hammer, did not have the potential to affect safety systems, or were anticipated events that should have been considered in the system design basis. Of the 24 water hammers, that had potential to affect safety systems, 12 occurred in the feedwater system. Eight of the feedwater system water hammers were related to the feedwater control valve. The damage reports indicate



Incident rate prior to commercial operation.

Incident rate during the first year of commercial operation.

Incident rate after the first year of commercial operation.

PWR normalized incident rate

Figure 2-1

that the greatest forces were generated by events occurring in the feedwater system. This is to be expected due to the large line size and the high fluid velocities and high fluid density in the feedwater system.

Of the 16 non-FCV events in the various systems (including FW) in the PWR plants, seven involved line voiding, two involved improper valve usage, one involved a drain malfunction, and one involved a design error. The causes of five of the events are unknown.

2.2.3 BWR Water Hammer Events

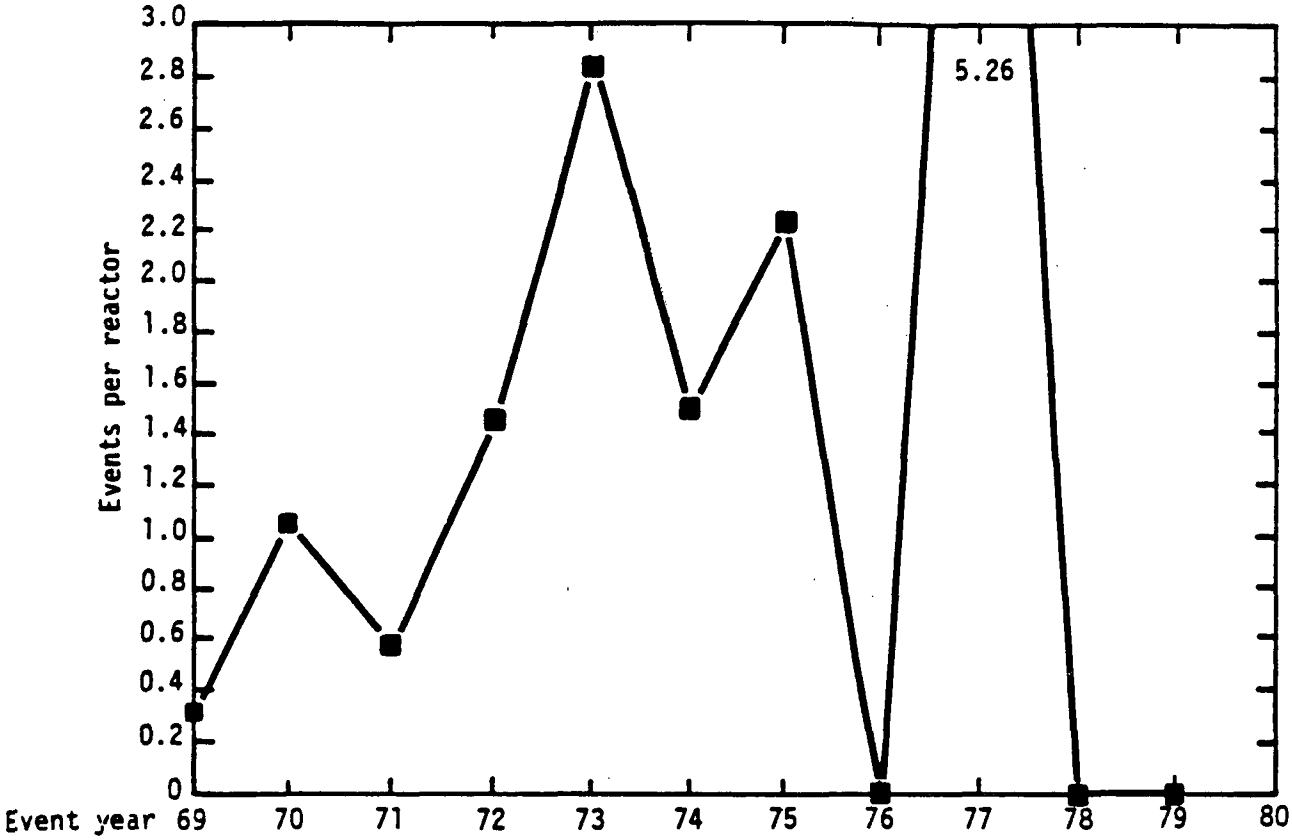
There were 81 BWR water hammer events reported in NUREG/CR-2059. None of the water hammer events placed a plant in a faulted or emergency condition. For most of the 81 events, damage was limited to the piping support system. For some events there was no reported damage. However, 18 of the water hammer events rendered a train of a safety system inoperable. These included two events in which flooding, caused by water hammers in nonsafety systems, rendered a safety system inoperable. No events damaged the integrity of the reactor coolant boundary. No events resulted in the loss of containment integrity nor release of radioactivity outside of the plant.

Twenty-nine (36%) of the events occurred prior to the plant's commercial operation date, at 15 different plants.

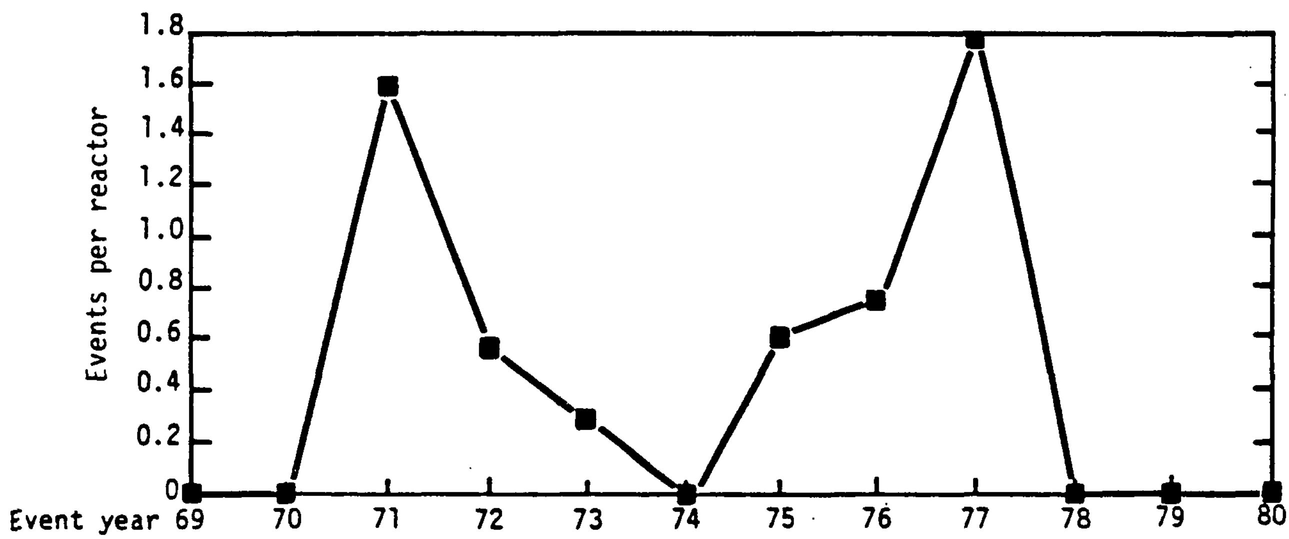
Thirteen (16%) of the events occurred within one year after the plant's commercial operation date at eight different plants.

Thirty-nine (48%) of the events occurred after the first year of the plant's commercial operation, at 17 different plants.

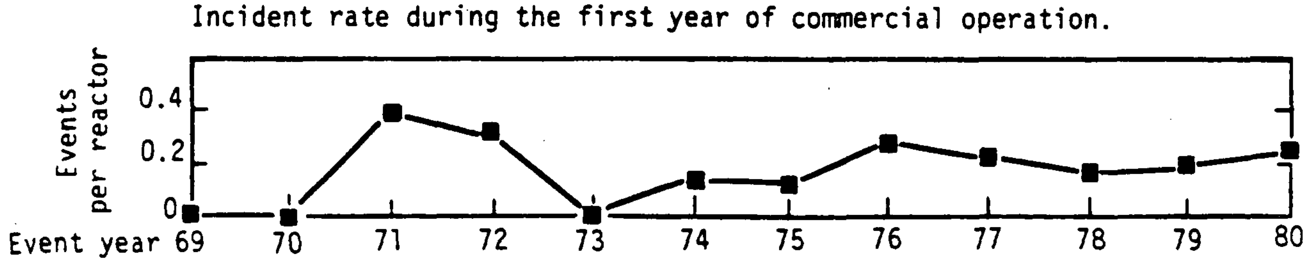
The incident rates (events per year per reactor) for events which occur after the first year of a plant's commercial operation are



Incident rate prior to commercial operation.



Incident rate during the first year of commercial operation.



Incident rate after the first year of commercial operation.

BWR normalized incident rate

82-268a

Figure 2-2

lower than rates of events which occur during the first year of a plant's commercial operation. Furthermore, the incident rates for events which occur during the first year of a plant's commercial operation are lower than the rates for events which occurred prior to a plant's commercial operation (see figure 2-2). The average incident rate for all plants after the first year of commercial operation is 0.22 events per year per reactor. Although the frequency of events is higher for BWR plants than PWR plants, a similar learning curve appears to exist for BWRs as does for PWRs.

Of the 81 reported events in the BWR plants, NUREG/CR-2781 considered only 69 to be unanticipated water hammer events that had the potential to affect safety systems. The other 12 events were either not water hammers, did not have the potential to affect safety systems, or were predictable events that should have been considered in the system design basis. Fifty-nine of the 69 water hammer events, having the potential to affect safety systems, occurred in four systems, namely, RHR (23), HPCI (20), core spray (9), and service cooling water (7). Other systems in which 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, which is discussed in more detail in section 2.4.1. 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 lines, steam-bubble collapse, and possibly some of the unknown events.

Other causes of water hammers having the potential to affect safety systems in BWR plants are: HPCI turbine steam line drain pot failure (seven), improper HPCI turbine steam line warmup (five), improper main steam line warmup (one), feedwater valve controller instability (three), reactor water entering isolation condenser (three), improper line slope (two), unknown and miscallaneous (nine).

2.3 Systems Evaluation

This section contains summary evaluations of water hammers occurring in various plant systems. Only those systems in which a significant number of events have been reported in NUREG/CR-2059 are discussed. Detailed evaluations for all systems reporting water hammers are found in NUREG/CR-2781.

2.3.1 PWR Systems

Twenty-seven of the 67 PWR events were SGWH events. SGWH is a steam condensation phenomenon and is discussed in more detail in section 2.4.2.

The feedwater system contributed to 13 of the 40 PWR non-steam-generator water hammer events reported in NUREG/CR-2059. The major cause of water hammer events in the feedwater systems was feedwater control valve (FCV) instability. FCVs contributed to eight of the ten system events for which a cause could be identified. FCV instability is the most serious non SGWH PWR concern and is discussed in section 2.4.3.

Four of the six steam (water) hammer events occurring in the main steam system were caused by valve closure. The valve closures resulted from such causes as spurious signals and excess flow check valve failure. The steam hammers resulting from such valve closures are similar to and bounded by those resulting from anticipated turbine stop valve closure events. The damage reported in a fifth event was the result of anticipated reaction forces from relief valve discharge opening. The damage from these five events could have been prevented by adequate support design. The loads from these events should have been incorporated into the design basis of the piping support systems in accordance with references 12, 13, 14, and 15. The only unanticipated water hammer event was caused by steam water entrainment due to improper operation of the MSIVs during line warmup.

There were five RCS pressurizer events reported in reference 1. These events should be considered anticipated hydraulic transients, in which forces are generated by a pressure wave passing through the discharge pipe following relief valve opening. The effect of pressurizer SRV actuation should have been incorporated into the component and pipe support system design basis in accordance with references 12, 13, 14, and 15.

There were four events in the emergency core cooling system (ECCS) at four different plants. Three of the events occurred in active safety injection subsystems during testing or plant operation and were classified as flow-into-voided-line events. Voiding is discussed in section 2.4.1. The fourth event was a steam-bubble collapse water hammer in an accumulator discharge line that occurred during testing while the plant was shutdown.

Two flow-into-voided-line events also occurred in essential cooling water systems.

Four events, occurring in the condenser system, did not have potential to affect safety systems and were possibly not water hammers.

2.3.2 BWR Systems

Twenty-three BWR RHR water hammer events were reported in NUREG/CR-2059. Flow into a voided line caused 16 events. The elevations of the RHR pump discharge lines are higher than the elevation of the pump suction source. This makes the system susceptible to leakage-induced voiding. Further discussion of voiding is presented in section 2.4.1. Six events were steam-bubble collapse events. Steam bubbles in the RHR pump discharge line to the RHR heat exchanger were caused by steam leakage through the steam isolation cooling line isolation valves. Steam-bubble collapse in water-filled lines is similar to line voiding, as discussed in section 2.4.1 One RHR event was a water entrainment water hammer, caused by improper warmup of the HPCI turbine inlet line, which is connected to the RHR steam condensing line.

A total of 20 HPCI system water hammer events were reported in NUREG/CR-2059. 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). Nine steam-water entrainment events occurred in turbine inlet lines and were caused by improper isolation valve usage (four events) and drain pot malfunctions (five events). HPCI isolation valves and drain pots are discussed in sections 2.4.4.1 and 2.4.4.2 respectively. Two steam water entrainment events in the turbine exhaust line were caused by drain level switch malfunctions. The twelfth steam-water entrainment events occurred in a gland seal condenser inlet line and was caused by operator error. The four steam-bubble collapse events were caused by vacuum, occurring in turbine exhaust lines (see section 2.4.5). The three flow-into-voided-line events and the one unknown event occurred in pump discharge lines.

Eight of the nine core spray events were caused by flow into a voided line. The other event was caused by steam-bubble collapse. The core spray system is highly susceptible to leakage-caused voiding, because its discharge lines are at higher elevations than its pump suction lines. Section 2.4.1 discusses voiding.

There were seven essential cooling water system water hammer events reported in reference 8. Two events also occurred in nonessential cooling water systems. Four of the essential system events were caused by flow into a voided line, two were caused by column separation and the cause of one event is unknown.

There were three water hammer and seven vibration incidents in BWR feedwater systems caused by regulating valves. Feedwater valves are discussed in more detail in section 2.4.3.

Six BWR main steam events were reported. One event was caused by an MSIV suddenly opening into an inadequately warmed up line. The other events were anticipated valve closure or relief valve discharge events or in nonsafety-related portions of the system. References 12, 13, 14, and 15 require that the design basis of the piping and support system include these anticipated loads.

There were four steam water entrainment events in the isolation condenser inlet line. One was caused by inadequate line drainage provisions. The other three were caused by high reactor water levels that permitted water to enter the inlet line (refer to section 2.4.4.3).

2.4 Generic Evaluations

The evaluations of references 8 and 9 determined that there are several generic causes of water hammer in nuclear plants. Some of these causes are peculiar to particular systems and others occur in several systems. These generic causes are discussed below.

2.4.1 Line Voiding

NUREG/CR-2781 has identified line voiding as the single greatest cause of water hammer events. Forty-nine percent (46 of 93) of the unanticipated non-SGWH water hammer events having the potential to affect safety systems reported in NUREG/CR-2059 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 and steam-bubble collapse. Possibly, some of the unknown events were caused by line voiding.

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 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 fluid in the discharge lines to leak back into the suppression pool. The open loop service water systems for both BWR and PWR plants are also supplied by sources below the level of the system lines. 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 second difference between BWR and PWR plants is the presence of steam-water interfaces in BWRs, permitting the leakage of steam bubbles into the water lines.

Studies that compared the HPCI, RCIC and AFW systems 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 occurring in 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. Keep-full systems continuously supply water to idle lines to prevent voiding. (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 valves. 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.

2.4.2 Steam Generator Water Hammer

Steam generator water hammer (SGWH) is defined as a steam-condensation-induced water hammer occurring in the secondary side of a PWR steam generator and the connecting feedwater line. Twenty-seven SGWH events were reported in NUREG/CR-2059, making SGWH the second most common type of water hammer. The mechanism for SGWH is described below (references 2 and 10).

Steam generators in most plants using Westinghouse and Combustion Engineering steam generators have a top feedring through which the feedwater is injected into the downcomer between the baffle and the outer shell. The top feedrings in the Westinghouse and Combustion Engineering designs originally had bottom holes to discharge the feedwater.

During certain plant transients, which occur as a part of plant shutdown operations, the SG water level may drop below the bottom of the feedring sparger. A bottom discharge feedring can be drained of water and filled with steam within 1 or 2 minutes after the feedring is uncovered if feedwater flow has been terminated. As the feedwater (usually highly subcooled auxiliary feedwater) enters the horizontal pipe run into the feedring, it flows under the steam blanket, as depicted in figure 2-3(a). Rapid steam condensation can occur at the interface between the steam and the subcooled feedwater, causing a countercurrent flow of steam over the top of the feedwater. Interaction forces between the steam and water can create enough turbulence to seal off a pocket of steam, as depicted in figure 2-3(b). Continued rapid condensation of steam in the pocket accelerates the slug of water into the void, as depicted in figure 2-3(c).

Acceleration forces on the water slug can be very large, because the pressure on one side is at steam generator pressure, initially in excess of 750 psi, while the pressure on the trapped vapor side can be greatly reduced, depending on condensation rate. As a result, the water slug can have a high velocity when it impacts against the incoming water column, and a pressure pulse is produced (figure 2-3(d). This constitutes one possible explanation of a steam generator water hammer. The magnitude of the pressure pulse and its propagation through the feedwater line depend on many factors. These include the steam void condensation rate, the initial volumes of the void and water slug, steam pressure in the steam generator, sonic velocity in the feedwater line, and piping geometry and layout (references 2 and 10). In a severe SGWH the pressure pulse may be as high as thousands of psi (references 2 and 10).

Most Babcock & Wilcox (B&W) steam generators have a top-discharge externally mounted main feedring (reference 10). Auxiliary feedwater

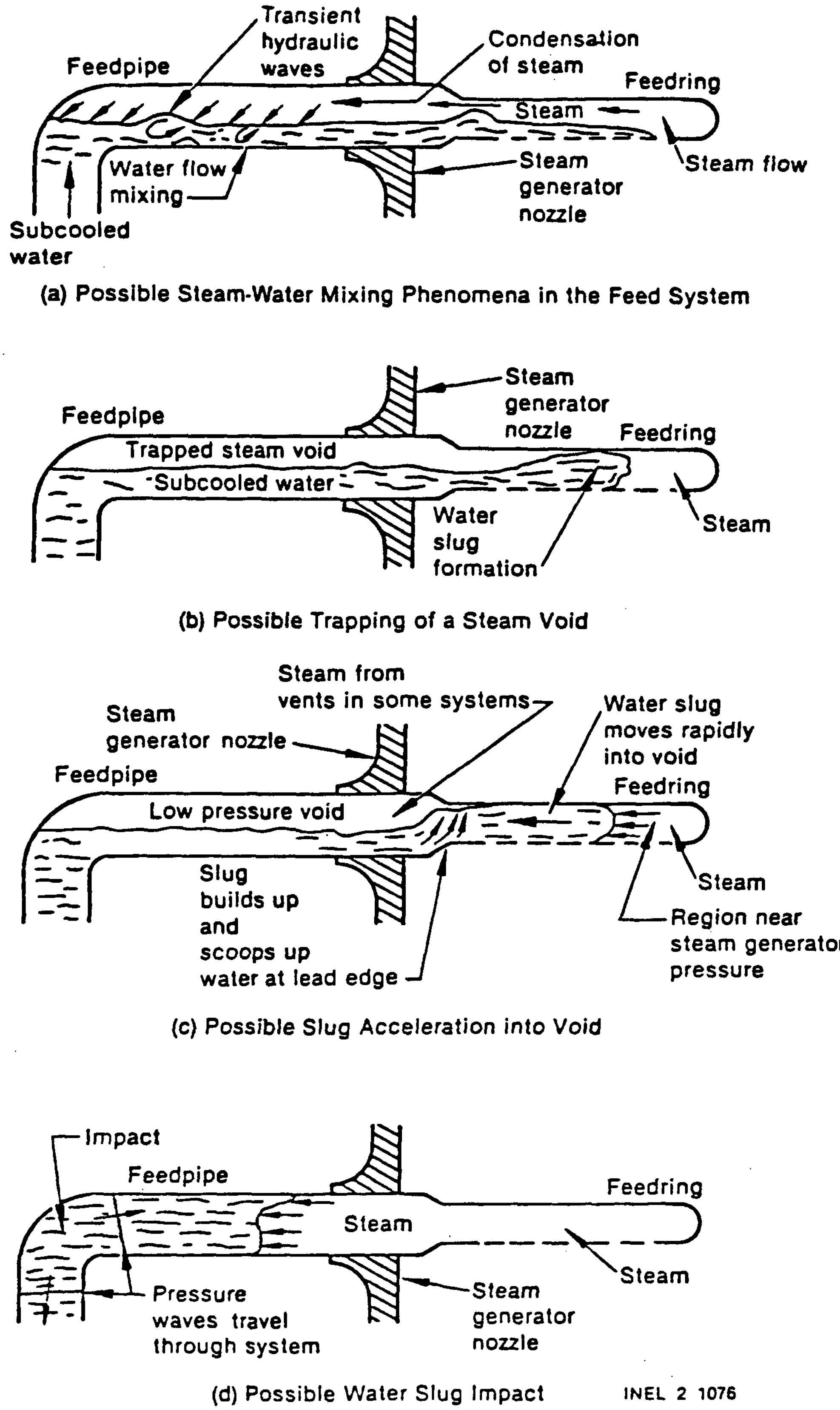


Figure 2-3 Possible sequential events leading to steam generator water hammer

is injected through a separate smaller diameter top-discharge externally mounted auxiliary feedring. B&W steam generators with externally mounted feedrings have not experienced damaging SGWH.

A different steam generator, called the preheat steam generator (PHSG) has recently been introduced. There are two feedwater nozzles in a preheat steam generator (references 11 and 16). The lower (main) nozzle is located at the preheat section and is used for feedwater supply to the steam generator during power operations when hot main feedwater is available. The upper (auxiliary) nozzle is located at the upper section of the steam generator and is used for supplying the feedwater when main feedwater is unavailable or is below a specified minimum temperature. The main nozzle is not used during low power operation because injecting cold feedwater through the main nozzle might cause steam bubble collapse in the preheat section of the steam generator if cold feedwater were injected into the preheat section (reference 11). In the Westinghouse PHSG design, neither the main feedwater nor the AFW line utilize a sparger. In the Combustion Engineering (CE) PHSG design, only the AFW line utilizes a sparger. The AFW sparger in later CE PHSG designs has a loop seal to preclude sparger draining. Many PHSGs also include tempering or bypass flow lines to keep the AFW line full during normal plant operation.

Generic and in-plant testing has shown that PHSG water hammer can be avoided during main feed flow through the use of appropriate procedures, that ensure only hot water is supplied through the main nozzle. Evaluations, reported in NUREG/CR-3090, show that the occurrence of SGWH during AFW operation of PHSG designs is highly unlikely. The occurrence of an SGWH event in a PHSG would require multiple component failures (including several check valves and operator errors). Even if such an event occurred, it is not expected to have an adverse effect on plant safety or AFW system operability.

2.4.3 Feedwater Control Valves

2.4.3.1 PWR Feedwater Control Valves

The major cause of non-SGWH water hammer events in PWR feedwater systems is feedwater control valve (FCV) instability. FCVs contributed to eight of the ten feedwater 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.

Generally, 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. Failure to verify FCV compatibility with the feedwater system has resulted in several designs in which the FCV is incompatible with the remainder of the feedwater system. The most common incompatibility has been valve oversizing. The incompatibility problem can be 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 tend to decrease valve stability. Systems containing turbine-driven feed pumps are more stable because feedwater flow is partially controlled by varying turbine speed.

2.4.3.2 BWR Feedwater Regulating Valves

Feedwater regulating valve instability and malfunctions caused three water hammers and seven events involving abnormal feedwater line vibration. 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 an internal feed back loop. Single-element (water level) control is used at low loads, because the three-element controller causes valves cycling at low loads. Cycling occurs because the steam flow signal is not accurate enough at low flow, causing instability in three-element control. The valve actuators were also strengthened to improve their ability to withstand cycling. There have been no BWR feedwater regulating valve incidents reported since the above modifications were made.

2.4.4 Steam Line Water Entrainment

2.4.4.1 Isolation Valve Operation

Improper operation of steam line isolation valves can cause water entrainment in steam lines. One BWR and one PWR main steam water hammer were caused by opening a main steam isolation valve (MSIV) too rapidly. The rapid valve opening in lines that were not completely warmed up caused steam condensation. The water slugs, formed by the condensate, caused water hammers upon impact with closed turbine stop valves.

Four HPCI turbine inlet line water hammers were caused by isolation valve operation. There are no provisions for draining the HPCI turbine steam supply 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 often has a "seal-in" control feature that causes the valve to open fully in a noninterruptible manner; 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. Liquid that was in the line between the valves can flow rapidly through the line and suddenly stop at the turbine stop valve, generating a water hammer.

2.4.4.2 Drain Pot Operation

Five water hammer events were caused by steam trap failures in the HPCI turbine inlet line. Two similar events occurred in the HPCI turbine exhaust line. HPCI is the only system in which water hammers caused by steam trap failures have been reported.

In the HPCI turbine steam supply line, 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 opening the bypass valve or providing any indication to the operator.

2.4.4.3 Isolation Condenser Inlet Line

Four water hammers occurred in isolation condenser inlet lines. One event was caused by improper line slope that did not permit condensate drainage. The other three events were caused by high reactor water levels that allowed water to be drawn into the normally steam-filled isolation condenser inlet line.

2.4.5 Turbine Exhaust Line Steam-Bubble Collapse

Five water hammers were caused by turbine exhaust line steam condensation. Four were in the HPCI system and one was in the RCIC system.

Unless the turbine exhaust line contains vacuum breakers, rapid steam condensation in the exhaust line can create a vacuum, 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. Short operational periods that can occur during testing are particulary conducive to condensation, because the turbine housing and exhaust line inside walls can remain cool and provide a subcooled condensing surface for the stagnant steam remaining in the pipe and turbine after shutdown.

2.4.6 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 them, 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 reduce their errors. To be most effective, efforts to reduce water hammer events should start before plant operation and the learning-by-experience period begins.

NUREG/CR-2781 reported the following general causes of operator-involved events:

- A lack of awareness often exists among plant operators concerning the possibility of water hammer events occurring in a particular system or subsystem, their causes, and what the results of those events would be. Plant operators 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.
- Sufficient information is often unavailable to the operators concerning the conditions in the system before the water hammer events occur.
- 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, it is important that plant operators, including personnel responsible for writing maintenance instructions and supervising maintenance activities, receive training in the causes and prevention of water hammer.

2.4.7 Operating and Maintenance Procedures

Many the water hammer events were reportedly 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, more 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, the potential for water hammer is generally not considered in either procedure writing or review (reference 9), although most procedures require line venting where appropriate.

2.4.8 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 and are predictable. As an example, turbine stop valves typically close in approximately 0.1 to 0.2 seconds, causing steam hammers. Other anticipated loads include sudden pump startup and filling of an empty piping system that cannot be kept full, such as an open loop cooling water system. 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 ASME B&PV Code section III, ANSI B31.1 and SRP 3.9.3 (references 12, 13, and 14).

2.4.9 Control Rod Drive (CRD) Hydraulic Lines

No water hammer events have been reported in CRD systems. However, analyses (reference 17) have shown that transient piping loads can be generated during scram CRD hydraulic system actuation. The results of these analyses were submitted as public comment to this document. 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 ASME B&PV Code section III, ANSI B31.1 and SRP 3.9.3 (references 12, 13, and 14).

2.5 Corrective Actions

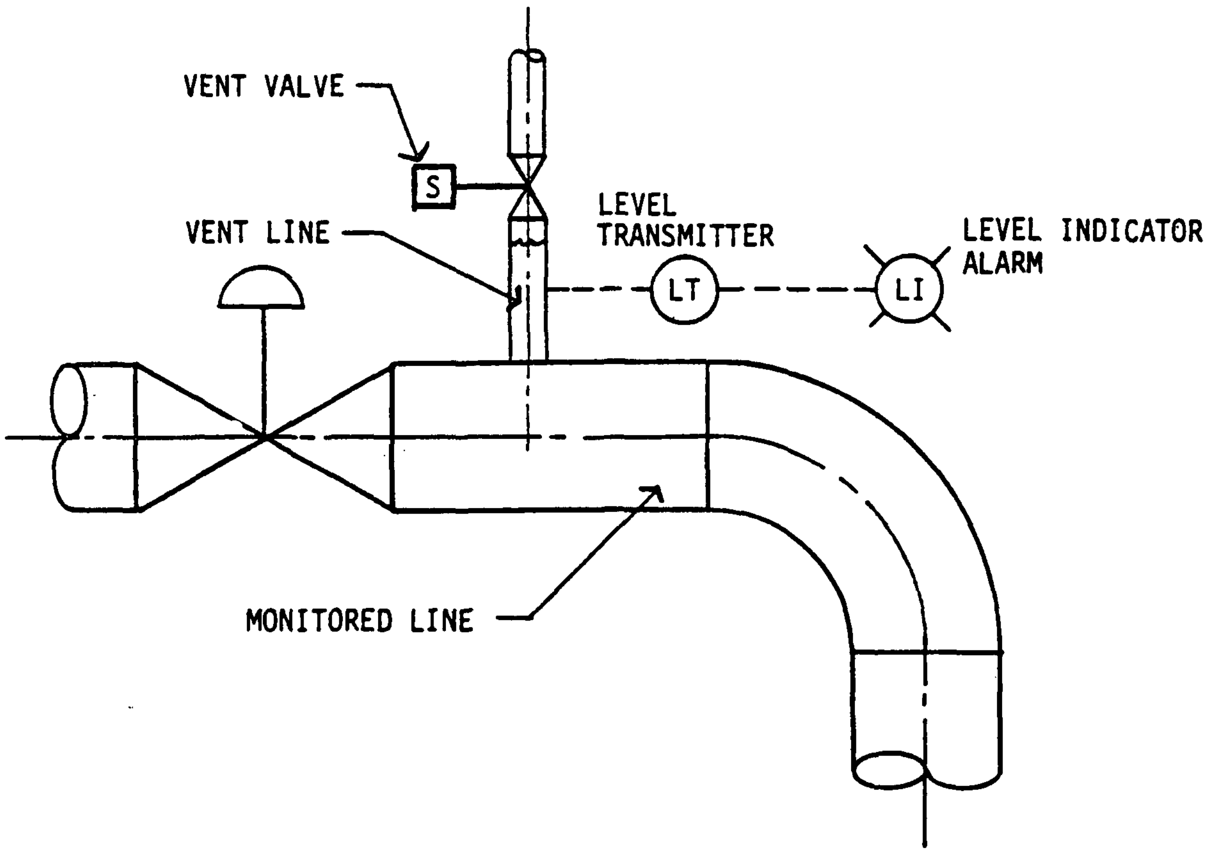
The corrective actions discussed below provide means to prevent or mitigate water hammers.

2.5.1 BWR Plants

2.5.1.1 Design Features

a. Void Detection. Void detection and alarm can be provided for the applicable systems. Void detection mechanisms could be located at those points in the normally liquid-filled lines where voids or steam bubbles could form or collect and have the potential to cause a damaging water hammer in a safety system. All void points that have the potential to cause damaging water hammers in a safety system could be monitored. No specific void detection designs are suggested; however, figures 2-4 and 2-5 show possible void detection design concepts.

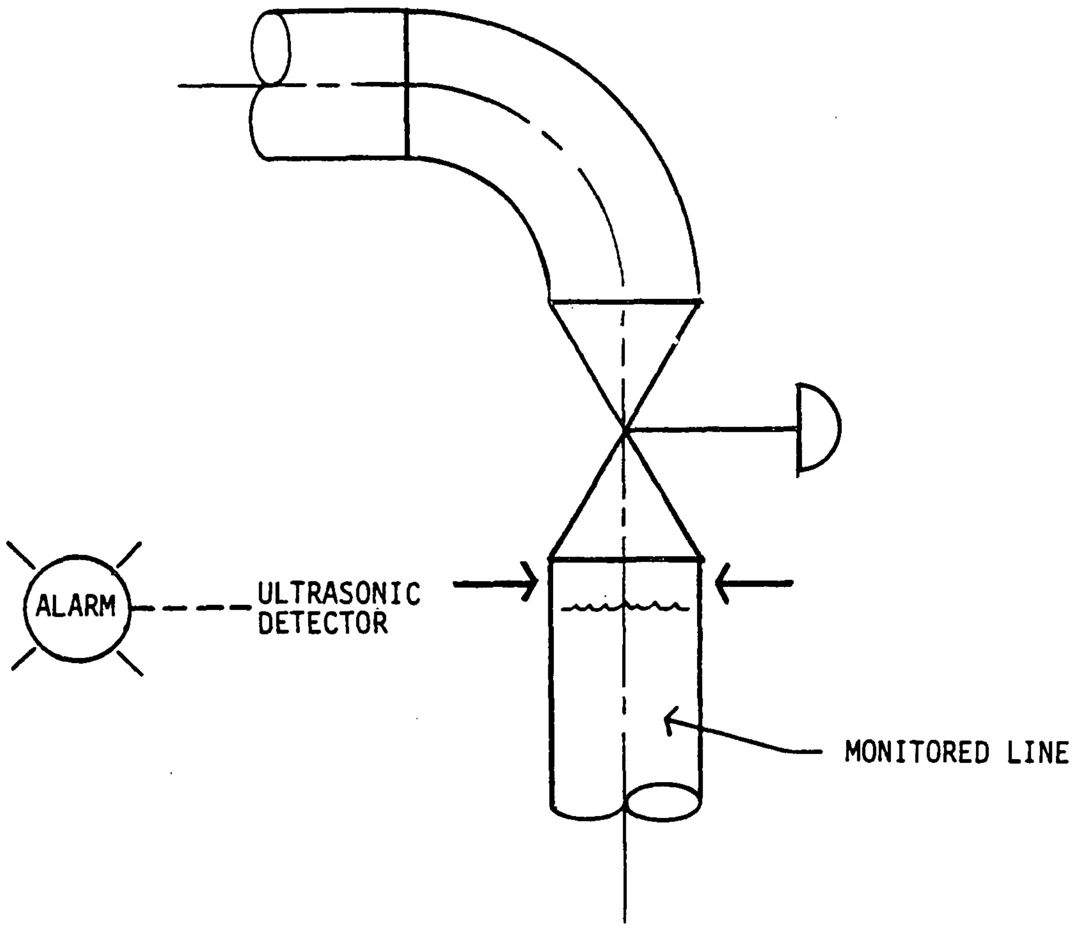
   The operability requirements for the applicable system should require rapid correction of voids having the potential to cause damaging safety-related water hammers. Use of the system other than for emergency use could be prohibited until these voids are vented and filled.



LEVEL TRANSMITTER IN VENT LINE DETECTS THE INCIPIENCE OF VOIDING AND PROVIDES ALARM.

FIGURE 2-4

CONCEPTUAL DESIGN OF POSSIBLE VOID DETECTION SYSTEM



ULTRASONIC DETECTOR, DETECTS VOID IN VERTICAL LINE AND PROVIDES ALARM.

FIGURE 2-5

CONCEPTUAL DESIGN OF POSSIBLE VOID DETECTION SYSTEM

It is difficult to define a maximum acceptable void size. Such a definition would require extensive case-specific transient analysis. Given the current state of the art, the results of such analysis would have limited credibility. Furthermore, the accurate determination of void size in a horizontal or sloped line would require a sophisticated measuring system. It may, therefore, be desirable to eliminate voids as soon after their inception as possible, rather than quantatively define and determine an acceptable size.

Voiding in open-loop service water systems may be considered acceptable if analysis has been performed to demonstrate that there will be no adverse effects if the system is started with voids present.

Applicable systems:
- o Residual heat removal
- o Core spray
- o High pressure coolant injection
- o Essential service water.

b. Keep-Full Systems. Continuously operating keep-full systems should be provided for filling voids in normally water-filled lines in the systems listed below. A jockey pump or a storage tank at a higher elevation than the lines of concern may be considered to be an adequate keep-full system.

Applicable systems:
- o Core spray
- o High-pressure coolant injection
- o Reactor core isolation cooling
- o Residual heat removal.

c. Filling Safety-Related, Open-Loop Service Water Systems. One of the following should be demonstrated for open-loop service water systems:

1. Voids can be filled within the required start time through a manually intiated fill system. This provision concerns 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 startup.
4. The system is designed to maintain function following a postulated water hammer event.

d. Venting. Venting provisions should be installed on the systems listed below. Venting should be provided at those 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.

Applicable systems:

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

e. Turbine Exhaust Line Vacuum Breaker. Vacuum breakers should be provided in the turbine exhaust lines that have a liquid interface.

Applicable Systems:

- o High-pressure coolant injection
- o Reactor core isolation cooling.

f. HPCI Steam Line Drain Pot.

1. The adequacy of the sizing of the HPCI drain pot system should be verified.
2. 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.

g. HPCI Turbine Inlet Line Isolation Valves. Neither valve should contain a seal-in feature on opening when in the manual mode. The inboard valve should be designed to permit gradual line warm up.

h. Feedwater Control Valve. The mutual compatibility of the feedwater control valve and the feedwater system should be verified. Valve design parameters, including actuator, flow coefficient (CV), and trim, should be 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 oscillation instability, vibrations, and water hammer.

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

i. Steam Hammer. The design basis for the main steam system components and piping supports should consider steam hammer resulting from the most rapid anticipated closure of all system valves, including the turbine stop valves.

j. Relief Valve Discharge. The design basis for the main steam system components and piping supports should consider fluid forces resulting from safety and relief valve operation.

k. Control Rod Drive. The design basis for the control rod drive (CRD) hydraulic system should include water hammer loads resulting from the worst case CRD actuation.

2.5.1.2 Operational Features

a. Operator Training. Plant operators, including personnel responsible for writing maintenance instructions and supervising maintenance activities, should receive training on the causes and prevention of water hammer. The training will make it possible for the operators to become aware of a potential water hammer situation and take preventive or corrective measures.

b. Operating and Maintenance Procedures. The licensee should review all operating, maintenance and testing procedures for the systems listed below for their appropriateness in preventing water hammer.

   Applicable systems:
   - Residual heat removal
   - High-pressure coolant injection
   - Core spray

- Essential service and cooling water
- Isolation condenser
- Feedwater
- Main steam.

c. Voiding. All potential void points which can cause a damaging water hammer in a safety system could be monitored. These systems should not be used when voids are present, other than for emergency use. Voids should be corrected as soon as possible.

Applicable systems:
- Residual heat removal
- High-pressure coolant injection
- Core spray
- Reactor core isolation cooling
- Essential service and cooling water.

Voiding in open-loop service water systems may be considered acceptable if analysis has been performed to demonstrate that there will be no adverse effects if the system is started with voids present.

d. HPCI Steam Line Drain Pot. The level indicators on the HPCI drain pot system should be checked for operability periodically and repaired if necessary.

e. HPCI Turbine Inlet Line Isolation Valves. Procedures should prohibit both opening the inboard isolation valve unless the normally open outboard isolation valve is fully open and closing the normally open outboard valve unless the inboard valve is fully closed. The provisions should apply when the valves are in the manual mode, for all operating conditions except cold shutdown.

2.5.2 PWR Plants

2.5.2.1 Design Features

a. Void Detection. The actions are the same as those listed for BWR plants in section 2.5.1.1.a.
Applicable systems:
- o Emergency core cooling (safety injection)
- o Essential service water.

b. Filling Safety-Related Open-Loop Service Water Systems. The actions are the same as those listed for BWR plants in section 2.5.1.1.c.

c. Venting. The actions are the same as those listed for BWR plants in section 2.5.1.1.d.
Applicable systems:
- o Emergency core cooling (safety injection)
- o Essential service water.

d. Feedwater Control Valves. The actions are the same as those listed for BWR plants in section 2.5.1.1.h.

e. Steam Hammer. The actions are the same as those listed for BWR plants in section 2.5.1.1.i.

f. Relief Valve Discharge. The actions are the same as those listed for BWR plants in section 2.5.1.1.j. Applicable systems:
- o Main steam
- o Reactor coolant (pressurizer).

g. Steam Generator Water Hammer

1. Top Feed Designs
   - o The feedring should incorporate top discharge J-tubes.
   - o The horizontal feedwater pipe entering the steam generator should be as short as possible, preferably less than seven feet long.
   - o Automatic initiation of AFW should be provided.

2. Preheater Designs
   - o Minimize the horizontal lengths of feedwater piping between the steam generator and the vertical run of piping by providing downward turning elbows immediately upstream of the main and auxiliary feedwater nozzles.
   - o Provide a check valve upstream of the auxiliary feedwater connection to the top feedwater line.
   - o Provide for maintaining the top feedwater line full at all times.
   - o Automatic initiation of AFW should be provided.

3. Once-Through Designs
   - o Provide auxiliary feedwater to the steam generator through an external header.
   - o Automatic initiation of AFW should be provided.

2.5.2.2 Operational Features

a. Operator Training. The actions are the same as those listed for BWR plants in section 2.5.1.2.a.

b. Operating and Maintenance Procedures. The actions are the same as those listed for BWR plants in section 2.5.1.2.b. Applicable systems:
   - o Emergency core cooling (safety injection)
   - o Feedwater
   - o Main steam
   - o Essential service and cooling water.

c. Steam Generator Water Hammer

1. Top Feed Designs

   - Auxiliary feedwater flow should be initiated as soon as possible following loss of main feed flow. This will prevent draining of the feedring.
   - Tests should be performed to verify that procedures for recovering steam generator water level will not result in SGWH.

2. Preheater Designs

   - Auxiliary feedwater flow should be initiated as soon as possible following loss of main feed flow. This will prevent draining of the upper feed line.
   - Tests should be performed to verify that procedures for recovering steam generator water level will not result in SGWH.
   - Tests should be performed to verify that the procedures for switching from the AFW nozzle to the main feed nozzle will not result in water hammer.
   - Maintain the top feedwater line full at all times.

3. Once-Through Designs

   - Auxiliary feedwater flow should be initiated as soon as possible following loss of main feed flow.
   - Tests should be performed to verify that procedures for recovering steam generator water level will not result in SGWH.

3.0 WATER HAMMER PREVENTION AND MITIGATION MEASURES

Section 3.0 provides additional details concerning the measures for water hammer prevention and mitigation contained in section 2.5. Because these measures may be applied to more than one system, the following generic subjects are identified:

- Void Detection Systems
- Keep Full Systems
- Venting
- Filling Safety-Related, Open-Loop Service Water Systems
- HPCI Turbine Inlet Line Valve
- Feedwater Control Valve and Controller
- HPCI and RCIC Turbine Exhaust Line Vacuum Breakers
- Steam Hammer
- Relief Valve Discharge
- HPCI Turbine Inlet Line Drain Pot Level Detection
- Operator Training
- Operating and Maintenance Procedures.

Water hammer assessments are generally performed during systems evaluations rather than during generic evaluations. Therefore, a systematic approach has been developed for using these findings. Table 3-1 summarizes for each BWR system the water hammer events that have occurred in the system and lists both design and operational means for water hammer prevention and mitigation. It is suggested that when reviewing a BWR system for water hammer considerations, the reviewer look up the system in table 3-1 to determine the appropriate review considerations and and then review the topics presented in sections 3.1 through 3.11.

Table 3-2 presents similar information for PWR systems and should be used in a similar manner to that described for BWR systems.

Tables 3-3 and 3-4 (for PWR and BWR) respectively identify which operating and maintenance procedure considerations discussed in section 3.12 are applicable to each plant system. Thus, for example, table 3-3 shows that the operating and maintenance procedures for PWR ECCS should address prevention of rapid valve motion, avoidance of voids in water-filled lines and components, and proper filling and venting of water-filled lines and components.

Finally, it should be noted that the findings set forth below represent the results of over 10 years' accumulated experience, design changes, etc., and therefore should benefit new designs.

3.1 Void Detection Systems

- A void detection system could be provided to detect voids at all high points in liquid-filled normally idle piping, where voids or steam bubbles could form through maintenance, operation, draining, out-leakage, gas evolvement, or in-leakage of steam of flashing fluid; and the potential for damaging water hammer events in safety systems exist.
- The void detection system could provide detection at all high points, including components and portions of lines isolated from other high points by valves.
- Void detection instrumentation can provide indication in the control room or locally. If local indication is provided, it should be demonstrated that radiation exposure to personnel will be As Low As Reasonably Achievable (ALARA).
- Void detection systems should be provided with means to test or verify the operability of the system.
- Void detection system displays and controls, if added to the control room, should not increase the potential for operator error. A human factors analysis should be performed, as required, taking into consideration the use of the information by an operator during both normal and abnormal plant conditions.

- Portions of piping or components that can only become voided during maintenance operations need not be continuously monitored, provided design or procedural measures have been implemented which will ensure that all voids will be eliminated prior to returning the piping or components to service.
- Operating procedures should incorporate a requirement that any void detected in the applicable systems (tables 3-1 and 3-2) shall be corrected as sooon as practical.

3.2 Keep-Full Systems

- A keep-full system should be provided as to prevent void formation in normally idle water-filled lines for the systems listed in tables 3-1 and 3-2.
- The keep-full system should be designed to operate continuously. An acceptable design is a continuously operating jockey pump or a storage tank with a water level at a higher elevation than the lines which it services.
- The keep-full system should be adequately sized to meet head and flow demands. The design of the keep-full system should account for line elevation, friction, and any pressure increases induced by valve in-leakage. The flow capacity of the keep-full system should accommodate the combined maximum leak rate of all the systems it services. Justifiable safety margins should be demonstrated in establishing head and flow demand values.
- The keep-full system should have the capability to provide detection of significant leakage in piping systems it services.
- Keep-full instrumentation should provide indication in the control room or locally. If local indication is provided, it should be demonstrated that radiation exposure to personnel will be As Low As Reasonably Achieveable (ALARA).
- The keep-full system should be provided with means to test or verify the operability of the system.

- The keep-full system displays and controls should not increase the potential for operator error. A human factors analysis should be performed, taking into consideration the use of the information by an operator during both normal and off-normal plant conditions.

3.3 <u>Venting</u>

- Vents should be provided to vent components and piping at all points specified in section 3.1.
- Vents in locations where voiding may occur during normal operation should be automatic, remotely operated, or designed for easy access and operator usage. Manual locally operated vents can be used for those locations where voiding can occur only during maintenance operations.
- Operating areas, where manual vents are located, shall be analyzed to assure adequate human operator environmental conditions including light, heat, access and radiation levels.
- The vent system design should provide the operator with the ability to determine the adequacy of a venting operation.
- The design and location of either remote or local controls for nonautomatic vents should be such that radiation releases will be As Low As Reasonably Achieveable (ALARA).
- The size of vent lines connected to the reactor coolant boundary should be kept smaller than the size corresponding to the definition of a LOCA (10 CFR part 50, appendix A) to avoid unnecessary challenges to the ECCS.
- Venting system displays and controls, if added to the control room, should not increase the potential for operator error. A human factors analysis should be performed, as required, taking into consideration the use of the information by an operator during both normal and abnormal plant conditions.
- Means should be provided to test or verify the operability of the vent system on a regular schedule.

3.4 Filling Safety-Related, Open-Loop Service Water Systems

One of the following should be met by safety-related, open-loop service water systems:

- For manually started systems, voids can be filled within the required start time. This provision concerns manually started systems only.

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

- 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.

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

3.5 HPCI Turbine Inlet Line Valve

- The HPCI turbine inlet line inboard or outboard isolation valves should not contain a "seal in" feature on opening when the valves are in the manual mode.
- The design of the The HPCI turbine inlet line inboard valve should permit gradual opening of the valve, as required, to permit acceptable line warmup.
- The operating procedures for the HPCI turbine inlet line should incorporate a requirement that prohibits closing the outboard isolation valve unless the inboard isolation valve is fully closed and opening the inboard isolation valve unless the outboard isolation valve is fully open, when the valves are in manual mode (for systems in which the outboard valve is normally open).

3.6 Feedwater Control Valve and Controller

- The feedwater control valve design should be reviewed to 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. Specifically, the following concerns should be addressed:
  - The feedwater control valve calculated or actual pressure drop should be compared with the valve specification to verify valve compatibility for the entire operating range of the valve.
  - If low flow bypass valves are used, the feedwater bypass valve and the feedwater control valve interaction should be reviewed to ensure that the lower end of the feedwater controllable operating range is below the level at which the low-flow bypass valves are used in place of the feedwater control valves.
  - Feedwater control valve stroke versus load characteristics, minimum steady-state operating loads, valve stability lower limit ranges, and other information affecting valve stability should be reviewed to verify that instability will not occur at the least open-valve steady-state operating point.
  - Values of the minimum static pressure in the feedwater control valve, the vapor pressure of the fluid, and other information affecting flashing should be reviewed to ensure that flashing will not occur at steady-state or normal transient conditions.
  - The sizing of the feedwater control valve should be compatible with the remainder of the feedwater and condensate systems. The valve should not be excessively oversized.
  - Feedwater control valve testing or operating experience data should be reviewed to verify that valve stroke characteristics will provide stable operation.

- Feedwater control valve design should be reviewed to verify that valve trim imbalance has been considered. Minimizing imbalance generally tends to increase valve stability.

o The feedwater controller valve control design should be reviewed to verify that the design precludes rapid valve actuation motion under any planned or spurious signal.

o The feedwater controller valve control design should be reviewed to ensure that it has been designed to prevent excessive ocillations and hunting.

o Test, analytical, or operating experience data should be reviewed to ascertain that neither valve nor control system components will fail suddenly due to normal usage or fatigue, resulting in rapid valve motion or flow rate changes.

3.7 HPCI and RCIC Turbine Exhaust Line Vacuum Breakers

o The HPCI and RCIC turbine exhaust lines should be provided with vacuum breakers to prevent vacuum formation in any portion of the exhaust line due to steam condensation.

o The vacuum breaker design and location should be reviewed to determine that all requirements for the reactor coolant pressure boundary are met.

o The vacuum breaker design should be reviewed to determine that the design precludes the introduction of water slugs from the suppression pool and rapid check valve closure.

o Vacuum breaker sizing should be reviewed to determine that the design accounts for the effects of condensation caused by an unwarmed exhaust line and water backflow.

3.8 HPCI Turbine Line Drain Pot Level Detection

o Drain systems should be provided for HPCI turbine lines to drain all condensate from the line low spots.

- The HPCI turbine lines' configurations and slopes should be reviewed to verify that all low spots drain to the drain system and that sufficient slope is provided in the configuration to ensure complete drainage.
- HPCI line drain systems should be reviewed to verify that the drain pots have been adequately sized to handle all expected condensate.
- The HPCI turbine inlet line drain system should be reviewed to verify that the design permits testing of the drain system with the turbine inlet line isolation valves open.
- HPCI turbine line drain systems should provide high-level indication in the control room. The systems' displays and controls should not increase the potential for operator error. A human factors analysis should be performed, as required, taking into consideration the use of the information by an operator during both normal and abnormal plant conditions. Means should be provided to test the operability of the HPCI line drain systems' level indicators and bypass valves.
- The procedures for the HPCI system should incorporate a requirement that the level indicators on the HPCI drain pot system should be checked on a regular schedule for operability.

3.9 Steam Hammer

The design bases for the main steam components and pipe supports should consider steam hammer forces resulting from the most rapid anticipated closure of all system valves, including the turbine stop valves.

3.10 Relief Valve Discharge

The design basis for the components and pipe supports of the applicable systems should consider fluid forces resulting from safety and relief valve operation, including those loads from water slugs where water seals are used or the valve lines normally contain subcooled or saturated liquid.

Applicable systems:

- o BWR
  - Main steam
- o PWR
  - Main steam
  - Reactor coolant system (pressurizer)

3.11 Plant Personnel Training

- o Training in the cause, effect, and prevention of water hammer should be provided to
  - licensed and nonlicensed operating personnel
  - maintenance personnel who maintain plant fluid systems where water hammer can occur
  - personnel who directly supervise these operating and maintenance personnel.
- o The training content should be relevant to the specific plant systems
- o Training should ensure that operating information pertinent to water hammer, originating both wthin and outside the utility organization, is continually supplied to oeprators and other personnel and is incorporated into training and retraining programs.

3.12 Operating and Maintenance Procedures

Operating and maintenance procedures for systems in which water hammer can occur should take into consideration the potential for water hammer. Operating and maintenance procedures should address:

- o Prevention of rapid valve motion
- o Introduction of voids into water-filled lines and components
- o Proper filling and venting of water-filled lines and components
- o Introduction of steam or heated water that can flash into water-filled lines and components

- o Introduction of water into steam-filled lines or components
- o Proper warmup of steam-filled lines
- o Proper drainage of steam-filled lines
- o The effects of valve alignments on line conditions.

3.13 Steam Generator Water Hammer (SGWH)

The following provisions of Branch Technical Position ASB 10-2 (reference 3) should be followed.

a. "Top Feed Designs

1. Prevent or delay water draining from the feedring following a drop in steam generator water level by means such as J-tubes.
2. Minimize the volume of feedwater piping external to the steam generator which could pocket steam using the shortest possible (less than seven feet) horizontal run of inlet piping to the steam generator feedring.
3. Perform tests acceptable to NRC to verify that unacceptable feedwater hammer will not occur using the plant operating procedures for normal and emergency restoration of steam generator water level following loss of normal feedwater and possible draining of the feedring. Provide the procedures for these tests for approval before conducting the tests.

b. Preheater Designs

1. Perform tests acceptable to NRC to verify that unacceptable feedwater hammer will not occur using plant operating procedures for normal and emergency restoration of steam generator water level following loss of normal feedwater. Also perform a water hammer test at *% of power by using feedwater through the auxiliary feedwater (top) nozzle at the lowest feedwater

*The power level at which feedwater flow is transferred from the auxiliary feedwater nozzle to the main feedwater nozzle.

temperature that the plant standard operating procedure (SOP) allows and then switching the feedwater at that temperature from the auxiliary feedwater nozzle to the main feedwater (bottom) nozzle by following the SOP.

2. Minimize the horizontal lengths of feedwater piping between the steam generator and the vertical run of piping by providing downward turning elbows immediately upstream of the main and auxiliary feedwater nozzles.
3. Provide a check valve upstream of the auxiliary feedwater connection to the top feedwater line.
4. Maintain the top feedwater line full at all times.

c. <u>Once-Through Designs (B&W)</u>

1. Provide auxiliary feedwater to the steam generator through an external header.
2. Perform tests acceptable to NRC to verify that unacceptable feedwater hammer will not occur using the plant operating procedures for normal and emergency restoration of steam generator water level following loss of normal feedwater. Provide the procedures for these tests for approval before conducting the tests."

d. NUREG 0737, paragraph II.E.1.2 (reference 15), requires automatic auxiliary feedwater system initiation. The requirements for the AFW system automatic initiation are contained in reference 15.

3.14 Control Rod Drive (CRD) Hydraulic Lines

The design basis for CRD hydraulic lines should consider the transient forces resulting from the worst case CRD system actuation.

TABLE 3-1. BWR System Water Hammer Causes and Preventive Measures.

SYSTEM	PRIMARY CAUSES OF WATER HAMMER	PREVENTIVE MEASURES (*)	
		DESIGN	PLANT OPERATION
RHR	Voiding, Steam-Bubble Collapse	Void Detection (3.1), Keep-full (3.2), Venting, (3.3)	Void Detection and Correction (3.1), Venting (3.2), Operating Procedures (3.12), Operator Training (3.11)
HPCI	Steam Water Entrainment, Turbine Inlet Valve Operation	No Opening Seal-in in Manual Mode (3.5a), Gradual Opening (3.5b)	Valve Opening Sequence (3.5c), Operator Training (3.11), Operating Procedures (3.12)
	Steam Water Entrainment Drain Pot Malfunction	Proper Drain System Including Drain Pot Sizing and Level Verification (3.8)	Verification of Drain Pot Level (3.8), Operating Procedures (3.12)
	Turbine Exhaust Line Bubble Collapse	Exhaust Line Vacuum Vacuum Breakers	
	Pump Discharge Line Voiding	Void Detection (3.1), Keep-Full System (3.2), Venting (3.3)	Void Detection and Correction (3.1), Venting (3.2), Operating Procedures (3.12), Operator Training (3.11)
Core Spray	Voiding Steam-Bubble Collapse	Void Detection (3.1), Keep-Full System (3.2), Venting (3.3)	Void Detection and Correction (3.1), Venting (3.2), Operating Procedures (3.12), Operator Training (3.11)
Essential Service Water	Voiding Column Separation	Void Detection (3.1), Keep-Full System (3.2), Venting (3.3), Open Loop Line Analysis (3.4)	Void Detection and Correction (3.1), Venting (3.2), Operating Procedures (3.12), Operator Training (3.11)

(*)Refers to section of this report providing details of preventive measures.

TABLE 3-1. Continued

SYSTEM	PRIMARY CAUSES OF WATER HAMMER	PREVENTIVE MEASURES	
		DESIGN	PLANT OPERATION
Main Steam	Steam Hammer Relief Valve Discharge	Valve Closure (3.9) and Relief Valve Discharge Loads (3.10)	
	Steam Water Entrainment		Operating Procedures (3.12), Operator Training (3.11)
Feedwater	Feedwater Control Valve Instability	Feedwater Controller Design Verification 3.6a, b, and c	
RCIC	Exhaust Line Steam Bubble Collapse	Exhaust Line Vacuum Breakers (3.7)	
Isolation Condenser	High Reactor Water Level		Operating Procedures (3.12), Operator Training (3.11)
**Control Rod Drive	Rapid Valve motion	Actuation Loads (3.14)	

**Control Rod Drive events have not been reported, but have been anlytically postulated.

TABLE 3-2. PWR System Water Hammer Causes and Preventive Measures.

SYSTEM	PRIMARY CAUSES OF WATER HAMMER	PREVENTIVE MEASURES (*) DESIGN	PLANT OPERATION
Feed-water	Feedwater Control Valve (FCV) Over-sizing & Instability	FCV Design Verification (3.6)	
	Unknown and Operator Error Induced Steam Bubble Collapse		Operating Procedures (3.12), Operator Training (3.11)
Main Steam	Steam Hammer (Valve Closure)	Include Valve Closure Loads in Pipe Support and Component Design Basis (3.9)	
	Relief Valve Discharge	Include Relief Valve Discharge Loads in Pipe Support and Components Design Basis (3.10)	
	Steam Water Entrainment, Unknown		Operating Procedures (3.12), Operator Training (3.11)
Reactor Coolant (Pressurizer)	Relief Valve Discharge	Include Relief Valve Discharge Loads in Pipe Support and Components Design Basis (3.10)	
RHR	Voiding	Venting (3.3)	Operating Procedures (3.12), Operator Training (3.11)
ECCS	Voiding	Venting (3.3), Void Detection(3.1)	Operating Procedures (3.12), Operator Training (3.11)
CVCS	Steam Bubble Collapse or Vibration		Operating Procedures (3.12), Operator Training (3.11)

TABLE 3-2. Continued

SYSTEM	PRIMARY CAUSES OF WATER HAMMER	PREVENTIVE MEASURES (*)	
		DESIGN	PLANT OPERATION
Essential Cooling Water	Voiding	Venting (3.1), Filling Essential Cooling Water (3.4), Analysis (3.4)	Filling Essential Cooling Water (3.4), Operating Procedures (3.12), Operator Training (3.11)
Steam Generator	Line Voiding Followed by Steam Bubble Collapse	BTP ASB 10-2 Provisions (3.13): Top Discharge, Short Line Lengths, External Header (B&W Only)	BTP ASB 10-2 Provisions (3.13): Testing, Keeping Line Full. Automatic AFW Initiation

(*)Refers to section of this report providing details of preventive measures.

TABLE 3-3

PWR Operating and Maintenance Procedure Water Hammer Considerations

System	Water Hammer Consideration	Rapid Valve Motion	Intro-duction of Voids	Filling and Venting	Steam or Hot Water in Water-Filled Lines & Components	Water Into Steam Lines	Steam Line Warmup	Steam Line Drainage	Valve Alignment
Feedwater		X			X				X
Main Steam						X	X	X	X
RHR		X	X	X					X
ECCS		X	X	X					X
CVCS		X	X	X	X				X
Cooling Water		X	X	X					X

TABLE 3-4

BWR Operating and Maintenance Procedure Water Hammer Considerations

System	Water Hammer Consideration	Rapid Valve Motion	Introduction of Voids	Filling and Venting	Steam or Hot Water in Water-Filled Lines & Components	Water Into Steam Lines	Steam Line Warmup	Steam Line Drainage	Valve Alignment
Core Spray			X	X					X
RHR		X	X	X	X	X	X		X
Isol. Cond.						X			
HPCI			X	X	X	X	X	X	X
RCIC			X	X	X	X	X	X	X
Main Steam						X	X	X	X
Feedwater		X			X				X
Cooling Water		X	X	X					X

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This report, which includes responses to public comments, summarizes key technical findings relevant to the Unresolved Safety Issue A-1, Water Hammer. These findings were derived from studies of reported water hammer occurrences and underlying causes and provide key insights into means to minimize or eliminate further water hammer occurrences. It should also be noted that this report does not represent a substitute for current rules and regulations.

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WASHINGTON, D.C. 20555

OFFICIAL BUSINESS
PENALTY FOR PRIVATE USE, $300

FOURTH-CLASS MAIL
POSTAGE & FEES PAID
USNRC
WASH. D. C.
PERMIT No G-67

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