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Water Hammer, Flow Induced Vibration and Safety/Relief Valve Loads

Prepared by P. Valandani, R. Uffer, D. Sexton

Quadrex Corporation

EG&G Idaho, Inc.

Prepared for
U.S. Nuclear Regulatory
Commission

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P. Valandani, R. Uffer, D. Sexton

Quadrex Corporation
Campbell, CA 95008

Under Subcontract to:
EG&G Idaho, Inc.
Idaho Falls, ID 83415

Prepared for
Division of Safety Technology
Office of Nuclear Reactor Regulation
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FOREWORD

PREPARED BY THE NRC STAFF

This report presents the results of an evaluation of current and recommended practices regarding the consideration of other dynamic loads in the design of nuclear piping systems. The evaluation was performed by the Quadrex Corporation for EG&G, Idaho as part of the NRC's technical efforts related to the Piping Review Committee. The findings and recommendations set forth in this report are those of the contractor and will be reviewed and considered by the NRC staff in its development of a position regarding the consideration of dynamic loads in piping design.

ABSTRACT

This report presents the results of an evaluation performed to determine current and recommended practices regarding the consideration of water hammer, flow-induced vibration and safety-relief valve loads in the design of nuclear power plant piping systems. Current practices were determined by a survey of industry experts. Recommended practices were determined by evaluating factors such as load magnitude and frequency content, system susceptibility to loads, frequency of load occurrence and safety effects of postulated piping damage.

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ACKNOWLEDGMENTS

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The contributions of Mr. Carl Obenchain (EG&G) and Mr. Aleck Serkiz (USNRC), who provided technical guidance for and review of the entire evaluation, are also gratefully acknowledged.

NOMENCLATURE

AE	Architect/Engineer
AFW	Auxiliary Feedwater
ANSI	American National Standard Institute
ARS	Amplified Response Spectra
ASME	American Society of Mechanical Engineers
BWR	Boiling Water Reactor
CRD	Control Rod Drive
CVCS	Chemical and Volume Control System
DLF	Dynamic Load Factor
ECCS	Emergency Core Cooling System
EPRI	Electric Power Research Institute
FCV	Feedwater (or Flow)Control Valve
FIV	Flow Induced Vibration
FSAR	Final Safety Analysis Report
HPCI	High-Pressure Coolant Injection
HPCS	High-Pressure Core Spray
KIP	1000 pounds force
LOCA	Loss-of-Coolant Accident
MOC	Method of Characteristics
MSIV	Main Steam Isolation Valve
NA	Not applicable
NRC	Nuclear Regulatory Commission
NSSS	Nuclear Steam Supply System
NUREG	Nuclear Regulatory Report
NUREG/CR	Nuclear Regulatory Contractor Report
OBE	Operating Base Earthquake
PWR	Pressurized Water Reactor
RCIC	Reactor Core Isolation Cooling
RCS	Reactor Coolant System
RHR	Residual Heat Removal

RPV	Reactor Pressure Vessel
SGWH	Steam Generator Water Hammer
SLC	Standby Liquid Control
SRP	Standard Review Plan
SRSS	Square Root Sum of the Squares
SRV	Safety/Relief Valve
SSE	Safe Shutdown Earthquake
TMI	Three Mile Island
TSV	Turbine Stop Valve
TSVC	Turbine Stop Valve Closure

EXECUTIVE SUMMARY

Evaluations were performed to determine current and recommended practices regarding the consideration of "other dynamic loads" in the design of nuclear power plant piping systems. The term "other dynamic loads" is used in this document to include piping loads caused by flow-induced vibration, safety-relief valve actuation and water (steam) hammers.

Current Status

- Flow induced vibration (FIV) loads are not included in piping analyses. Flow induced vibration is generally not considered as a load but is always monitored during pre-operational and start-up testing.
- The effects of main steam and pressurizer safety relief valve (SRV) loads are required to be and are included in the design basis of piping.
- Anticipated water and steam hammer loads that are significant, such as those caused by turbine stop valve closure or trip of an essential cooling water pump, are included in the design basis of piping systems.
- Unanticipated water hammers such as those caused by void filling, steam bubble collapse and water entrainment are not included in the piping design basis.

Recommended Treatment of "Other Dynamic Loads"

- The current practice of preoperational testing for FIV and taking corrective action as necessary should be continued.

- SRV loads should be included in the design basis of piping and combined with other loads using square root sum of the squares (SRSS) methodology.

- The potential for the occurrence of all water hammers should be considered in developing system design specifications.

- Anticipated water (steam) hammer loads, such as those caused by valve closure, that are significant should be included in the design basis of piping and combined with other loads using SRSS methodology.

- Unanticipated water hammer loads, such as those caused by steam bubble collapse (steam generator feedwater) and void filling, need not be included in the design basis of piping support systems for the following reasons. First, the frequency of occurrence of unanticipated water hammer events is low when compared to other dynamic events such as SRV actuation and valve closure. Secondly, these events have resulted in limited damage, have not resulted in a radioactive release and have not had a significant effect on public risk. Finally, designing for unanticipated water hammer events would require installing numerous massive pipe supports that could decrease plant safety by restricting access for inspection and maintenance.

- Efforts to minimize the occurrence of unanticipated water hammer should continue.

1.0 INTRODUCTION

This report presents the results of evaluations performed to determine current and recommended practices for the consideration of "other dynamic loads" in the design of nuclear power plant piping systems. In this document "other dynamic loads" represents water hammer, steam hammer, flow induced vibration (FIV) and safety-relief valve (SRV) loads. The evaluations were performed by Quadrex Corporation for EG&G, Idaho, Incorporated. The report was prepared for use by the USNRC's Piping Review Committee in developing a position regarding the consideration of "other dynamic loads and load combinations" in piping system designs.

The scope of these studies was limited to performing a survey of current industry practices and to performing qualitative and semiquantitative analyses of various factors important to the consideration of dynamic piping loads.

Current industry practices and code requirements are presented in section 2. Section 3 presents analyses of the individual factors that are important in developing recommendations regarding the consideration of other dynamic loads in piping system design. Significant findings, including recommendations, are presented in section 4.

2.0 CURRENT PRACTICES

A review of code requirements and an industrial survey were performed to determine the current industry practices in treating "other dynamic loads."

2.1 Definitions

- Water (Steam) Hammer - These are loads that result from an abrupt change in flow velocity due to sudden stoppage of the flow. Examples are flow changes caused by sudden valve closure or the collapse of a void.
- Flow-Induced Vibration (FIV) - These are oscillatory, quasi-steady loads produced by pressure oscillations or flow oscillations introduced by a system component such as a pump or an oscillating valve. Self-excitation of the flow can also occur by mechanisms such as vibration of an elbow, which creates an oscillatory flow.
- Safety-Relief Valve (SRV) - When an SRV is actuated, fluid is suddenly introduced in the discharge line at a high velocity. If the discharge line is long, a pressure wave travels down the line creating axial loads in pipe segments. For the case where the discharge line is short (discharge to atmosphere) there are no segment forces but there is a thrust force acting on the valve body.

2.2 Current Code and Regulatory Requirements

- The ASME Boiler and Pressure Vessel Code, section III, Article NB-3620 (reference 1) and the NRC Standard Review Plan (SRP) (reference 2) require that "other dynamic loads" be considered in the design of piping systems.

- SRP section 3.9.3 specifies that loads due to system operating transients be combined with OBE and with sustained loads and the system must meet a service limit not greater than Level B.

- NUREG 0484 (reference 3) specifies the conditions under which the responses of other dynamic loads may be combined by the SRSS method.

- Article NB3622.3 of the ASME Boiler and Pressure Vessel Code (reference 1), ANSI-ASME OM-3 (reference 16) and USNRC Regulatory Guide 1.68 (reference 4) require that system vibration be within acceptable levels.

- Regulatory Guide 1.68 (reference 4) states:
  "The start-up phase of the initial test program should include at least tests and measurements to verify the following:

  - vibration levels for system components and piping are within pre-determined limits.

  - piping movements during heatup and steady state and transient operation are within pre-determined limits."

- NB-3622.3 of ASME section III (reference 1) code states:
  "NB-3622.3 Vibration. Piping shall be arranged and supported so that vibration will be minimized. The designer shall be responsible, by design and by observation under start-up or initial service conditions for ensuring that vibration of piping systems is within acceptable levels."

2.3 Industry Survey

A survey was made to determine how "other dynamic loads" are currently being considered.

A total of twelve experts (see acknowledgments) from eight nuclear industry companies and organizations were surveyed and asked the same set of questions. Of the twelve, two had only Boiling Water Reactor (BWR) experience, four had only Pressurized Water Reactor (PWR) experience and the remaining six had both BWR and PWR experience. Their affiliations consisted of two NSSS vendors, four Architect Engineering (AE) firms, one utility/AE and one consulting firm.

After defining "other dynamic loads", five questions were asked regarding the application of those loads to safety-related systems. Following is a list of the questions and a summary of the responses to each question:

- Which "other dynamic loads" are addressed?
- In which systems are these loads considered?
- How are these "other dynamic loads" obtained?
- How significant are these loads compared with other loads?
- How are they combined with other loads?

2.3.1 Survey Responses

- Which "Other Dynamic Loads" are Addressed?

  All respondents indicated that water hammer, steam hammer and SRV loads are addressed. The degree to which the respondents addressed these loads varied in some areas. Flow induced vibration is generally not considered as a load but is always monitored during pre-operational and start-up testing and corrective action is taken as necessary.

- In Which Systems are These Loads Considered?

Water hammer loads caused by rapid check valve closure are always considered in the design of feedwater lines for both BWR and PWR plants. The use of a slow closing check valve was mentioned as a possible way of mitigating water hammer in feedwater lines. Pump seizure was mentioned by one respondent as a possible source of water hammer.

Two respondents said they analyze BWR Control Rod Drive (CRD) piping and CRD withdraw lines for water hammer. The valves on both lines are fast opening valves (10 - 60 msec.). The accumulator which feeds the CRD lines is at 1500 psi. The withdraw line valve opens slightly ahead of the CRD inlet valve. The withdraw line discharges to a tank which is at atmospheric pressure. Thus, both valves have a large pressure difference across them which causes a pressure wave downstream of the valve, when the valve is suddenly opened.

Other lines that are sometimes evaluated for water hammer include containment spray lines (PWR), feedwater lines (PWR) and steam generator blowdown lines (PWR). The mechanisms for events in these lines are: sudden valve opening for containment spray, bubble collapse for feedwater lines and flashing for steam generator blowdown lines. The magnitude of the resulting loads depend on the assumptions made in the analysis. Feedwater bypass lines (PWR) and reactor vessel head vent lines (PWR post TMI) are sometimes analyzed for water hammer. One respondent evaluates steamlines on Babcock & Wilcox PWR plants for potential water hammers caused by postulated steam generator overfill.

Generally, all systems are checked for potential water hammers caused by quick opening or quick closing valves, check valves and pump trip. If there is a likelihood of water hammer, the resulting loads are evaluated and considered. Except for the cases mentioned above, the magnitudes of these loads are not significant because of either the small line size or the long valve opening and closing times.

Steam hammer is always considered in the main steamline analysis. Steam hammer loads are significant for the turbine stop valve closure (TSVC). The closure of main steamline isolation valves (MSIV) is also considered, but the loads are bounded by the TSVC case, because MSIV closure time is an order of magnitude larger than TSV closure time (e.g. 4 seconds vs. 0.1 seconds).

Safety-relief valve loads are always considered for main steamlines (BWR and PWR) and for pressurizer relief lines (PWR). The loads due to relief valve actuation on the RHR heat exchanger (BWR) have not been considered significant in the past, but one respondent does analyze the discharge line of that relief valve for SRV loads.

A respondent also stated that other quick acting valves, such as turbine bypass valves, cause dynamic loads in the discharge piping and these loads are considered.

Loads caused by flow-induced vibration are not considered in the initial design stage of piping support systems. It is assumed that any vibration observed during start-up testing will be eliminated through hardware modification and/or changes in the operating procedures. Generally, large safety-related lines are not expected to have FIV problems. Sometimes small lines are subject to FIV and the problem is fixed by adding supports or vibration dampers.

- <u>How are These "Other Dynamic Loads" Obtained?</u>

  Water hammer and steam hammer loads are generally calculated by using computer codes which are variations of the public domain program RELAP (references 17 and 18), or based on the method of characteristics (MOC). Some companies use computer codes that are available through service bureaus, such as WAVENET (reference 19). Some use bounding hand calculations for the preliminary evaluation of these phenomena. In general, these loads are calculated by a thermo-hydraulic group and applied by the piping analysis group, but some piping groups have the thermo-hydraulic expertise to develop these loads.

RELAP type programs are also used by some companies for SRV loads. In one case the SRV loads were supplied to the AE by the NSSS vendor, in another case the NSSS vendor supplied the piping stresses caused by SRV loads. EPRI test results (reference 20) form the basis for most PWR pressurizer SRV load definitions. According to one respondent, the EPRI SRV Test results for SRV's with loop seals* were greater than originally calculated. The difference was attributed to the shorter than expected valve opening time (60 msec. vs. 1 1/2 sec. maximum opening time allowed by the NSSS vendor). In some plants, a decision was made to remove the loop seals and replace the valves with new ones which were qualified for steam service.

Water hammer, steam hammer and SRV loads are generally developed in the form of force-time histories suitable for dynamic analysis of the piping system. An equivalent static analysis is usually performed on PWR main steam line SRV's that discharge to the atmosphere. An appropriate dynamic load factor (DLF), is applied to the static load to account for transient effects.

BWR main steam line SRVs have long discharge lines that discharge under water. Method of characteristics (MOC) computer programs are

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* A loop seal is a "U" shaped piping section at the upstream side of the relief valve that is maintained full of water to protect the valve from steam erosion.

usually used to calculate force time histories for BWR main steam line SRVs.

For other safety/relief valves, both the flow-rate and the discharge pipe size are smaller and therefore the loads are generally much smaller than those for main steamline SRV's. For these other SRV's, simplified conservative analyses that bound the problem are usually performed. More rigorous and accurate time history analyses are only used if necessary.

- How Significant are These Loads Compared with Other Loads?
  The significance of a load with respect to this question only concerns its effect on the design of the piping support system.

  Water hammer and steam hammer loads are large when mass flow-rate is high, valve closing time is short and the pipe is of relatively large size. Water hammer loads due to check valve closure following a postulated pipe rupture are significant for feedwater lines. Steam hammer loads resulting from main steamline stop valve (TSV) closures are large. The loads due to MSIV closure are generally much smaller than TSV loads due to longer valve closing times. One respondent described the calculated water hammer loads for the CRD line and the CRD withdraw line as significant and attributed the large magnitude of these loads to the conservatisms inherent in the computer program used for the analysis. It was pointed out by another respondent, that the steam hammer loads for the main steam line are particularly significant near the stop valve and attenuate away from the valve. Both water hammer and steam hammer produce axial loads that need to be reacted by axial restraints. These loads are therefore significant with respect to the design of axial restraints.

  SRV loads are significant for PWR pressurizer SRVs (particularly those with a loop seal) and for BWR main steamline SRVs. There is a broad range of discharge line sizes, SRV capacities, discharge line geometries, and submergences in BWR plants. For these reasons and the fact that the loads also depend on the initial conditions in the discharge line including pipe temperature, water leg lengths, and the amount of air in the line, it is not possible to come up with a typical value for the SRV loads in BWR plants. However, it is generally agreed that these loads are the major loads controlling the design of axial restraints for the SRV discharge lines. The SRV loads for PWR pressurizer SRV's with a loop seal are very large. In fact, some PWR owners opted to remove the loop seals and switch to a different type of SRV because the loads were "unmanageable" otherwise.

o How are They Combined with Other Loads?

The details of event classification, load combination, and acceptance criteria could not be obtained during the survey. In two cases it was said that the load combination is done in accordance with the Final Safety Analysis Report (FSAR), which is plant dependent.

More specific responses were obtained from three respondents who said that stresses due to these dynamic loads are added to those due to seismic loads using the square root of the sum of the squares (SRSS) method and the result is absolute value summed with the stresses due to static loads. Table 2-1 summarizes how one organization considers steam hammer caused by turbine stop valve closure.

2.3.2 Overview of Current Practice

Four types of "other dynamic loads" are discussed separately. They are flow induced vibration, safety/relief valve loads, anticipated water (steam) hammer and unanticipated water hammer.

Table 2-1

Typical Methodology for Considering Turbine Stop Valve Closure Loads

Condition	Load Combination
Service Levels A & B	Static Loads: Pressure, Thermal and Dead Weight $[(TSVC)^2 + (OBE1 + OBE2)^2]^{1/2}$
Service Level C	$P + W + [(OBE1)^2 + (TSVC)^2]^{1/2}$
Service Level D	$P + W + [(SSE1)^2 + (TSVC)^2]^{1/2}$

P = Operating pressure load associated with that load combination
W = Dead weight load
OBE1 = Inertia loads due to Operating Basis Earthquake (OBE)
OBE2 = Anchor displacement loads due to Operating Basis Earthquake (OBE)
SSE1 = Inertia loads due to Safe Shutdown Earthquake (SSE)
TSVC = Steam hammer load due to turbine stop valve closure

2.3.2.1 Flow-Induced Vibration (FIV).

Flow-induced vibration in piping is not amenable to accurate a priori analytical prediction and is generally monitored during start-up testing. If vibration levels are found to exceed acceptable limits, mitigation of vibration amplitudes is effected through system and/or support modifications and/or changes in the operating procedures. If necessary, the system is analyzed to ensure the design adequacy for the measured levels of vibration. This practice is in accordance with ASME code, ANSI-ASME OM-3 (reference 16) requirements and the requirements of REG. Guide 1.68 (reference 4).

2.3.2.2 Safety/Relief Valve (SRV) Loads.

SRV loads for the main-steam line SRV's and pressurizer SRV's (PWR) are obtained by analysis or by using test data. For BWR plants, the SRV loads are time-histories, which are used in the dynamic analysis of the piping system. For open discharge SRV's, the maximum thrust is calculated and applied with the proper dynamic load factor (DLF). The loads for pressurizer SRV's with loop seals are based on a combination of analysis and test data. For SRV's on other systems, where the loads are generally much lower than for the above mentioned SRV's, bounding calculations are performed to obtain conservative loads.

SRV loads are used in dynamic or equivalent static dynamic piping analysis to obtain the piping response. The responses are combined with OBE responses by the SRSS method and the result is absolute summed with the response of sustained loads.

The definition and application of the SRV loads are in accordance with SRP section 3.9.3 (reference 2).

2.3.2.3 Water (Steam) Hammer

Water hammer due to check valve closure following a postulated break in the feedwater line is a postulated water hammer event and is considered in the design of that system. In BWR plants, the control rod drive (CRD) piping and CRD withdraw lines are analyzed for water hammer. Other anticipated water hammer cases, generally due to pump trip, are considered to be bounded by other loads, or are of negligible magnitude.

In those cases where water hammer loads are significant enough to be considered, they are combined with other loads in accordance with section 3.9.3 of SRP.

The only anticipated steam hammer event of any significance occurs in main steam lines because of turbine stop valve closure. The loads due to this event are calculated and combined with other loads according to section 3.9.3 of the SRP.

2.3.2.4 Unanticipated Water Hammer

An unanticipated water or steam hammer is one that would not be expected from a component or system operating in the manner for which it was designed. Examples of unanticipated water hammer include those caused by steam bubble collapse, void filling and water entrainment in steam lines. Unanticipated water hammers are generally not included in the design basis of piping system. Increasing awareness of water hammer and its effects has led the industry to implement system modifications and changes in operating procedures that minimize the probability of occurrence of unanticipated water hammer events. These changes and modifications are discussed in NUREG/CR-2781 (reference 5). A combination of hardware modifications and changes in operating procedures continues to reduce the frequency of occurrence of such events. For example, steam generator water hammer (SGWH) is an unanticipated steam bubble collapse water hammer capable of producing very large loads. However, the frequency of occurrence of SGWH has been substantially reduced through design modifications and changes in operating procedures.

3.0 EVALUATION OF OTHER DYNAMIC LOADS

An evaluation was performed to determine the significance and appropriat treatment of other dynamic loads in the design of piping support systems. In order to perform this evaluation the following factors were considered:

- Susceptibility of safety systems to "other dynamic loads"
- Potential for simultaneous occurrence of multiple loads
- Effects of piping failure
- Frequency of occurrence
- Load magnitudes
- Frequency content

An attempt was made to provide quantitative answers in those areas where data or analysis were available.

3.1 System Susceptibility

This section contains evaluations of PWR and BWR plant safety systems and safety portions of non-safety systems which may be susceptible to the "other dynamic loads" identified earlier. The evaluations were based on system design and operational aspects and operational history. Information for the water hammer portion of this evaluation was obtained from references 5, 14 and 21.

Safety systems termed susceptible to "other dynamic loads" include those where the potential for these loads exists because of operation or design aspects of the system and actual occurrences. The likelihood that some of these "other dynamic loads", such as water hammer, will occur is low. In fact, some of the postulated events have not occurred. This is partially due to an increased awareness of their existence and the implementation of appropriate design and operational considerations. Some of these considerations are discussed below.

3.1.1 PWR Systems

The results of the PWR safety systems "other dynamic loads" susceptibility evaluation are summarized in table 3-1. The safety systems, which types of "other dynamic loads" these systems may be susceptible to, and any actual occurrence of the water hammer based on operational history, are presented. Flow induced vibrational loads, listed, are generally caused by pump operation. Vibrational loads caused by improper valve installation are not addressed in this report, because they can be remedied without consideration of additional pipe supports. For this reason, all safety systems shown in table 3-1 which have a pump have been identified as being susceptible to vibrational loads. Small water relief valves on piping and equipment mounted relief valves do not affect the piping. Therefore, these valves are not considered in table 3-1. Brief discussions of each system, identified dynamic loads, and some of the design or operational features which reduce the potential for "other dynamic loads" occurrences are presented below.

Feedwater System

Safety related portions of the feedwater system include all piping and components from the steam generators up to and including the outermost containment isolation valve. This portion of the feedwater system is susceptible to water hammer loads. These water hammers, which include those caused by steam generator water hammers (SGWH) and feedwater control valve (FCV) instability, comprise the majority of all reported PWR water hammers.

Table 3-1

PWR Safety Systems Susceptible to Other Dynamic Loads

PWR Plant Safety System	Vibration Potential	SRV Discharge	Potential for Water-Hammer Load	Actual Water Hammer Occurrence	Potential Steam-Hammer
Feedwater system			✓	✓	
Reactor coolant system	✓	✓	✓		
Main steam system		✓	✓	✓	✓
Auxiliary feed water system	✓		✓	✓	
Residual heat removal system	✓		✓	✓	
Chemical and volume control system	✓		✓	✓	
ECCS safety injection system	✓		✓	✓	
Containment spray system	✓		✓		
Auxiliary cooling water system	✓		✓	✓	
Spent fuel pool cooling system	✓		✓		

Extensive evaluations of the causes and implementation of measures for the prevention of SGWH and FCV water hammers have already been performed.

Reactor Coolant System

The reactor coolant system, including the pressurizer SRV discharge line, is susceptible to vibrational, safety relief valve discharge, and water hammer loads. Reactor coolant pump operation under various plant operating conditions can induce vibrational loads. Pump cavitation due to possible forced circulation of a two phase fluid mixture under accident conditions could also induce vibrational loads.

Safety relief valve discharge loads occur at the pressurizer relief valve and in the valve discharge line. These loads are much larger if there is a water slug discharged to the pressurizer relief tank. If there is vacuum formation in discharge lines which have no vacuum breakers, void formation can occur after relief valve discharge and draw relief tank water back into the discharge line causing a water hammer.

Main Steam System

Safety related portions of the main steam system include the valves and piping from the secondary side of the steam generator up to and including the outermost containment isolation (main steam isolation) valve. This includes the safety and power operated relief valves located between the steam generator and containment isolation (main steam isolation) valves and portions of the steam generator blowdown system. This portion of the main steam system is susceptible to safety relief valve discharge, water hammer, and steam hammer loads. Safety relief valve discharge loading will occur any time the safety or power operated relief valves are activated. Steam hammer will occur following sudden closure of the main steam isolation or turbine stop valves. Steam-water entrainment water hammer can occur if procedures are not properly followed during system warm-up.

Auxiliary Feedwater System

The auxiliary feedwater system (AFW) is susceptible to vibrational and water hammer loads. Vibrational loads can be generated by auxiliary feedwater pumps and turbine operation. The system is susceptible to water hammer at the steam generator inlet if steam backleakage into the line occurs and cold water is then introduced.

Residual Heat Removal System

Vibrational and water hammer loads can occur in the residual heat removal system. Vibrational loads can occur due to pump operation. Water hammer could occur due to steam-bubble collapse in high temperature pump suction lines or flow initiation into lines which may have become voided due to system standby status.

Chemical and Volume Control System

The chemical and volume control system (CVCS) is susceptible to vibrational and water hammer loads. In addition to normal vibrational loads caused by pump operation, vibrations may occur in the letdown line during normal plant operation, as observed in some plants. Water hammer may occur in the letdown line if the temperature is too high. This causes flashing which in turn initiates the formation of steam bubbles. The likelihood of this event however, is small because of the large thermal capacity of the letdown heat exchangers.

ECCS Safety Injection System

The safety injection system is susceptible to pump induced vibrational and water hammer induced dynamic loads. Water hammer occurrence is typically caused by the filling of a voided line and can be prevented by proper system operation and venting.

Containment Spray System

The containment spray system is a standby system and, as such, is susceptible to water hammer caused by the filling of a voided line. Proper venting and fill will prevent water hammer occurrences and no such occurrences have been reported. Vibration can occur from pump operation.

Auxiliary Cooling Water Systems

The potential for other dynamic loads in closed loop standby systems is the same as for the residual heat removal system. During standby or maintenance modes, portions of the system that cooldown can generate voids. Proper venting of these voids prior to startup lowers the potential for water hammer.

Spent Fuel Pool Cooling

The potential for other dynamic loads in the spent fuel pool cooling system is similar to that for the residual heat removal system.

3.1.2 BWR Systems

The results of the BWR safety systems "other dynamic loads" susceptibility evaluation are summarized in Table 3-2. Safety systems which have the potential for the occurrence of "other dynamic loads" are identified as susceptible and are included in Table 3-2.

Core Spray System

The core spray system is susceptible to vibrational and water hammer loads caused by pump operation and flow into a voided line, respectively. Keep full systems are currently standard for most plants and along with proper venting procedures will prevent void formation.

Table 3-2

BWR Safety Systems Susceptible to Other Dynamic Loads

BWR Plant Safety System	Vibration Potential	SRV Discharge	Water-Hammer Potential	Water-Hammer Occurrence	Steam-Hammer Potential
Feedwater	✓		✓	✓	
Residual Heat Removal System	✓		✓	✓	
High Pressure Coolant Inj. System	✓		✓	✓	
Reactor Core Isolation Cooling System	✓		✓	✓	
Safety Related Portions of the Main Steam Sys.		✓	✓	✓	✓
Auxiliary Cooling Water Systems	✓		✓	✓	
Reactor Recirculation System	✓				
Standby Liquid Control System	✓				
Spent Fuel Pool Cooling System	✓		✓		
Safety Related Portion of the Reactor Water Cleanup System	✓		✓	✓	
Control Rod Drive			✓		
Isolation Condenser	✓		✓	✓	

Residual Heat Removal System

Water hammer events have been recorded for all modes of RHR operation except suppression pool cooling. The most common cause of water hammer is flow into a voided line. Keep full systems to prevent flow into voided lines are used for water hammer prevention. Additionally, the system is susceptible to vibrational loads. Relief valve discharge lines can experience loads. However, relief valve loads have no effect on main RHR piping.

High Pressure Coolant Injection System

The high pressure coolant injection (HPCI) system is susceptible to vibrational loads caused by pump and turbine operation, and water hammer in the turbine steam supply, steam exhaust, and pump discharge lines. Collection of water in the steam lines or voiding of the pump fluid lines are potential sources of water hammer. Keep full systems to prevent flow into voided lines and vacuum breakers on steam lines which discharge into the suppression pool are used for water hammer prevention.

The HPCI system has been replaced by the high pressure core spray system (HPCS) in new plants. The HPCS system is susceptible to the same loads as the core spray system and should employ the same preventive methods.

Reactor Core Isolation Cooling System

The reactor core isolation cooling (RCIC) system is susceptible to the same types of other dynamic loads, as the high pressure coolant injection system. Keep full systems to prevent flow into voided lines and vacuum breakers on steam lines which discharge into the suppression pool are used for water hammer prevention.

Feedwater System

Safety related portions of the feedwater system include all piping and components from the reactor pressure vessel (RPV) up to and including the outermost containment isolation valve in system piping. This portion of the feedwater system is susceptible to water hammer type dynamic loads. These water hammer and vibration loads are caused by feedwater control valve (FCV) instability. Modifications to the FCV actuator and control system have eliminated FCV water hammer and vibrational loads.

Main Steam System

Safety related portions of the main steam system include the steam lines, main steam isolation valves (MSIVs), piping from the MSIVs up to but not including the turbine stop and control valves, and safety relief valves. This portion of the system is susceptible to safety relief valve discharge, water hammer, and steam hammer. Steam hammer loads are caused by fast closure of mainsteam line isolation or turbine stop valves. Water hammers, caused by condensate build-up due to improper functioning of drain pots or improper line warm-up, are possible.

Auxiliary Cooling Water Systems

Auxiliary cooling water systems are susceptible to pump induced vibrational and water hammer loads. Water hammer may be caused by flow into voided lines. Void formation can occur due to improper filling and venting. Drainage and pump trip can also cause voiding and column separation in open loop systems.

Reactor Recirculation System

The reactor recirculation system is susceptible to reactor recirculation pump induced vibration.

Standby Liquid Control System

Pump induced vibrational loads can potentially occur in the standby liquid control system. No reported incidents of water hammer have occurred in this system.

Spent Fuel Pool Cooling System

The spent fuel pool cooling system is susceptible to the same types of load considerations as the PWR spent fuel pool cooling system. These loads include pump induced vibrational and water hammer loads.

Reactor Water Cleanup System

Safety related portions of the reactor water cleanup system include those portions that form the let-down and make-up loops which come into contact with the reactor coolant system pressure boundary. During standby periods, reduced water temperatures can cause shrinkage and create voids in the system, thus creating the potential for water hammer. One reported incident of this type has occurred.

Control Rod Drive System

The control rod drive (CRD) system is susceptible to water hammer loads caused by the rapid flow changes occurring during scram actuation (reference 12).

Isolation Condenser

Isolation condensers undergo vibration during use. The isolation condenser system inlet line is susceptible to water hammer if the reactor water level is allowed to rise high enough to entrain water in the steam inlet line.

The addition of a high reactor water level feedwater pump trip prevents this type of water hammer.

3.2 Simultaneous Dynamic Loads

The potential for multiple "other dynamic loads" to occur simultaneously with each other or with seismic loads was evaluated. Four multiple load combinations were identified, two of which are addressed in further detail in the following sections. The four combinations include normally occurring vibrational loads in conjunction with a seismic event, infrequently occurring other dynamic loads in conjunction with a seismic event, seismic induced events followed by infrequently occurring other dynamic loads, and other multiple dynamic load combinations excluding seismic events.

Of all the "other dynamic loads" which can occur simultaneously with a seismic event, normally occurring vibrational loads have the highest likelihood of occurring in conjunction with a seismic event. Normally occurring vibrational loads include those which are induced by pump operation during normal plant conditions. Susceptible systems in PWR plants, during normal operation, include the reactor coolant, chemical and volume control, auxiliary cooling water, and spent fuel cooling systems. The auxiliary feedwater (AFW) and residual heat removal systems (RHR) are susceptible during plant startup and shutdown. However, since the AFW and RHR pumps do not operate continuously when a plant is at power, the likelihood of a concurrent seismic event is less. The pumps in BWR plants which operate normally include those of the reactor recirculation, auxiliary cooling water, and spent fuel pool cooling systems. During startup and shutdown operations, the RHR system also operates.

Simultaneous occurrences of infrequent and short duration loads, such as water hammer, in conjunction with a seismic event, are considered to be of a very low probability and have not been evaluated further (see section 3.4.3). Other dynamic loads, such as main steam relief valve loads may occur as a result of a seismic event and are discussed below.

Seismic Induced Events

Seismic events may initiate events such as turbine trip or loss of offsite power. Following a turbine trip, the main isolation and turbine stop valves can close, inducing a steam hammer, followed by SRV discharges from the main steam systems. For PWR systems, this scenario can also include pressurizer relief valve discharge loads. Though not induced simultaneously, the steam hammer and SRV actuation loads can occur while the seismic event is underway. Since seismic events are not of long duration, loads caused by safety system initiation would generally start following the seismic event. However, if safety system initiation occurred during the seismic event, the only other dynamic load consideration in combination with the seismic event would be flow induced vibration. Table 3-3 summarizes this discussion and presents the most likely seismic and other dynamic load combinations for the systems identified above.

Other Multiple Dynamic Load Combination

Combinations of other dynamic loads, excluding seismic events, are presented in Table 3-4. These conditions include those which are most likely due to the nature of the load.

Table 3-3

Potential Seismic Induced Multiple Load Combinations

Seismic Induced Initiating Event	BWR Other Dynamic Loads Concurrent w/Seismic Event	BWR Systems Involved	PWR Other Dynamic Loads Concurrent w/Seismic Event	PWR Systems Involved
Loss of Offsite Power	Steam Hammer	Main Steam	Steam Hammer	Main Steam
	SRV Discharge	Main Steam Reactor Recirculation	SRV Discharge	Main Steam Reactor Coolant
	Vibrational(3) (Flow Induced)	ECCS(1) Reactor Recirculation(2)	Vibrational(3) (Flow Induced)	Reactor Coolant(2) Emergency Feedwater System(1)
Turbine Trip	Steam Hammer	Main Steam	Steam Hammer	Main Steam
	SVR Discharge	Main Steam Reactor Recirculation	SRV Discharge	Main Steam Reactor Coolant
	Vibrational(3) (Flow Induced)	ECCS(1) Reactor Recirculation(2)	Vibrational(3) (Flow Induced)	Reactor Coolant(2) Auxiliary Feedwater System(1)

Footnotes:

1. Vibrational loads concurrent with seismic loads only if ECCS or standby system initiation occurs prior to completion of the seismic event.
2. Pump induced vibrational loading until coast down of tripped pump.
3. Significant vibrational loads are identified and eliminated during preoperational testing.

Table 3-4

Potential Multiple Other Dynamic Load Combinations

Other Dynamic Load Combinations	BWR Systems Impacted	Cause for BWR Load Combinations	PWR Systems Impacted	Cause for PWR Load Combinations
Steam Hammer and Relief Valve Discharge	Main Steam	Turbine Stop Valve and/or main steam isolation valve closure	Main Steam	Turbine stop valve and/or main steam isolation valve closure
Pump Induced Vibration and Water Hammer	All standby and intermittent operating systems susceptible to flow into voided line water hammer	Flow into voided lines after pump start	All standby and intermittent operating systems susceptible to flow into voided line water hammer	Flow into voided lines after pump start

3.3 Piping Failure Safety Significance

A qualitative piping failure safety significance evaluation was performed for the PWR and BWR plant safety systems identified as susceptible to other dynamic loads. A worst case single piping or component failure which could disable the system under evaluation was postulated even though such events have not occurred . The consequences of the postulated failure on plant safety were then assessed. These assessments took into consideration such factors as the normal operating status of the system, the system's design function, alternate paths to ensure plant safety, and redundant or alternate backup systems.

Systems were grouped by normal operability status. Those which function continuously or intermittently during full power operation comprise one group. Standby systems, which are called upon for plant startup, shutdown, or mitigation of abnormal conditions, comprise the other group.

3.3.1 PWR Safety Systems

PWR safety systems which operate continuously or intermittently during full power operation (see table 3-5) include the feedwater, reactor coolant, mainsteam, chemical and volume control, auxiliary cooling water, and spent fuel pool cooling systems. Evaluations of worst case piping failures for these systems show that the postulated failure will not prevent safe plant shutdown. Events and shutdown paths are identified in table 3-5.

Systems normally in standby include the auxiliary feedwater, residual heat removal, ECCS, and containment spray systems. Other than those portions of these systems which may be used for normal plant startup, shutdown, or abnormal conditions, the only time these systems operate is during testing. Most of the water hammer events in standby systems occurred during testing (reference 5). Failure of these systems during plant startup or shutdown will not prevent safe shutdown because redundant systems are provided to perform their function. Failure during testing will have no direct impact on plant safety.

3.3.2 BWR Safety Systems

BWR safety systems which operate continuously or intermittently during full power operation (see table 3-6) include the main steam, auxiliary cooling water, reactor recirculation, spent fuel pool cooling, and reactor water cleanup systems. No postulated single worst case failure in these systems will prevent safe plant shutdown. Alternate plant shutdown paths are identified in table 3-6.

Systems normally in standby include the core spray, high pressure coolant injection, reactor core isolation cooling, isolation condenser and standby liquid control system. Other than plant startup, shutdown, abnormal, or test conditions, these systems are in a standby mode. If system failure occurs during testing, there is no direct impact on plant safety because:

- The system is isolated from the reactor coolant boundary
- The probability of a system demand is low
- There are back-up systems to replace the failed system

Most of the water hammer events in these systems occurred during testing (reference 5). A failure during testing will have no direct impact on plant safety.

Table 3-5

PWR Piping Failures Safety Significance Evaluation

System	Postulated Worst Case[1] Failure	Alternate or Redundant Shutdown Paths
Normally Operating:		
Feedwater	Loss of normal feedwater	Auxiliary feedwater and all plant safety systems remain available for safe plant shutdown.
Reactor Coolant	Loss of coolant accident (LOCA)	ECCS and all other plant safety systems remain available.
Main steam	Main steam line break	ECCS and all other plant safety systems remain available.
Chemical & Volume Control System	LOCA Failure of boron concentration control capability	ECCS and all other plant safety systems remain available. Control rods and reactor protection systems remain available.
Auxiliary Cooling Water	Loss of one cooling water loop.	Redundant loop remains available.
Spent Fuel Pool Cooling	Loss of one cooling loop	Redundant loop remains available. Total spent fuel pool cooling loss has no immediate adverse effect on plant safety.

Footnotes:

1. The postulated failures have never occurred. However, postulations were made to determine worst consequences.

2. No direct safety impact on plant if failure occurs during testing.

Table 3-5 (Cont'd)

PWR Piping Failures Safety Significance Evaluation

System	Postulated Worst Case[(1)] Failure	Alternate or Redundant Shutdown Paths
Standby (2):		
Auxiliary Feedwater	Loss of auxiliary feedwater to one steam generator	Normal feedwater, residual heat removal, auxiliary feedwater, to other steam generators, and other safety systems remain available.
Residual Heat Removal	Loss of residual heat removal	Auxiliary feedwater and other long term cooling systems remain available.
ECCS	Loss of one safety injection loop.	Other safety injection loop or loops and accumulators remain available.
Containment Spray	Loss of one containment spray loop.	Redundant containment spray loop remains available.

Footnotes:

1. The postulated failures have never occurred. However, postulations were made to determine worst consequences.
2. No direct safety impact on plant if failure occurs during testing.

Table 3-6

BWR Piping Failures Safety Significance Evaluation

System	Postulated Worst Case[1] Failure	Alternate or Redundant Shutdown Paths
Normally Operating:		
Feedwater	Loss of feedwater	ECCS systems available.
Residual Heat Removal	Loss of one loop.	Redundant cooling loop and other ECCS remain available.
Main Steam	Main steam line break.	ECCS and all other plant safety systems remain available.
Auxiliary Cooling	Loss of one cooling water loop.	Redundant loop remains available.
Reactor Recirculation	Loss of coolant accident (LOCA)	ECCS and all other plant safety systems remain available.
Spent Fuel Pool Cooling	Loss of one cooling water loop	Redundant loop remains available. Total spent fuel pool cooling loss has no immediate adverse effect on plant safety.
Reactor Water Cleanup	LOCA	ECCS and all other plant safety systems remain available.
Standby (2):		
Core Spray	Loss of one core spray loop.	Redundant core spray loop remains available.
High Pressure Coolant Injection (HPCI)	Loss of HPCI	Automatic depressurization system and other ECCS remain available.

Footnotes:

1. The postulated failures have never occurred. However, postulations were made to determine worst consequences.

2. No direct safety impact on plant if failure occurs during testing.

Table 3-6 (Cont'd)

BWR Piping Failures Safety Significance Evaluation

System	Postulated Worst Case(1) Failure	Alternate or Redundant Shutdown Paths
Reactor Core Isolation Cooling (RCIC)	Loss of RCIC	ECCS and other plant shutdown systems remain available.
Standby Liquid Control (SLC)	Loss of SLC	Control rods and reactor protection system remain available.
Control Rod Drive	Loss of insert line	Standby liquid control system available
Isolation	LOCA, loss of isolation condenser cooling capability	Feedwater and plant safety systems remain available.

Footnotes:

1. The postulated failures have never occurred. However, postulations were made to determine worst consequences.
2. No direct safety impact on plant if failure occurs during testing.

3.4 Frequency of Occurrence

Estimates of frequencies of occurrence of other dynamic loads in PWR and BWR plant safety systems were obtained from references 5, 8, 9, and 10 and are presented in tables 3-7 and 3-8. All systems identified as susceptible to other dynamic loads are included. Dynamic loads to which a system is not susceptible are identified as "NA" (not applicable). Values are presented for vibrational, water hammer, SRV discharge, and steam hammer loads.

The occurrence frequency data presented in tables 3-7 and 3-8 are approximate estimates only and should not be used as exact values. This is particularly true for SRV discharge and steam hammers. Water hammer data is more accurate. There are two main purposes for listing these frequencies. The first is to illustrate relative frequency of occurrence. As an example, it can be seen that relief valve discharge and TSV induced steam hammers occur several orders of magnitude more frequently than water hammer. The second purpose is to provide reasonable estimates of occurrence for use in estimates of the probability of single and multiple occurrences.

The data is considered to be of limited accuracy because reporting is not required for the events which occur frequently, such as SRV discharge and TSV closure. Frequencies reported for these events are estimates. Reporting is required for water hammer events in safety systems. Therefore, these values are more accurate than those for SRV discharge and TSV closure. It should be noted, however, that while the water hammer data is drawn fom a large time and demand data base, the data generally includes very few events in most systems.

Vibrational loads include those which are induced by pump operation. Flow instabilities due to valve misalignment are not included. As indicated in tables 3-7 and 3-8, when a system is operational it is subjected to vibrational loads. The number of occurrences is dependent on the number of demands for system operation. Vibrational loads are not significant unless caused by component malfunction.

3.4.1 SRV Discharge and Steam Hammer Frequencies

Frequencies of main steam system SRV discharge, pressurizer SRV discharge and steam hammers due to TSV closure are presented on a per year basis. A frequency of occurrence range was obtained by using values from references 10 and 15. Frequencies were obtained by summing all initiating events (transient) frequencies from reference 10 with the seismic and LOCA initiating event frequencies obtained from reference 9. These values are the upper end of the ranges specified, because they conservatively assume that all plant initiating events result in steam hammer and SRV discharges. The lower end of the ranges were obtained using the data on the number of SRV operational demands from reference 15. These values are based on actual forced reactor scrams over a three year period for various plants. The study assumes that all BWR reactor scram incidents and one half of PWR reactor scrams result in SRV actuation. Applying the same ratios to the values obtained from reference 10 for the upper end of the frequency range, a frequency range of 3 - 5 per year for PWRs is obtained. Allowing an additional three SRV actuations per year for normal shutdown periods during which the main condenser is unavailable, a range of 6 - 8 SRV discharges per year is obtained.

It should be pointed out that each SRV discharge may consist of multiple valve actuations and, in the case of BWRs, consecutive actuation of one or more valves.

3.4.2 Water Hammer Frequencies

Water hammer frequencies are presented in tables 3-7 (PWR) and 3-8 (BWR) on a per year basis for systems such as main steam and feedwater that operate continually, and on a per demand basis for systems such as RHR, RCIC, and AFW that only operate occasionally.

Water hammer frequencies are based on events reported in references 5, 8, and 14. PWR water hammer frequencies are based on data for all PWRs. BWR water hammer frequencies for systems such as feedwater and main steam, that are common to all BWRs, are based on all BWR plants. BWR water hammer frequencies for systems such as RHR, HPCI, and RCIC, that are not included in all plants, are based only on BWR3 and BWR4 plants. The water hammer frequencies for isolation condenser are based on plants having isolation condensers.

3.4.3 Probability of Seismic Plus Other Dynamic Loads

SRV discharge and TSV closure can be induced by some, but not all, seismic events. Therefore, the probability of simultaneous occurrence of a seismic event and SRV discharge and TSV closure is approximately the same as the probability of a seismic event (i.e. 4×10^{-3}/year).

The probability of simultaneous occurrence of a seismic event and a totally unrelated water hammer in a system which is not actuated by a seismic event is also very small. The durations of both seismic events and water hammers are on the order of one minute. If the frequency of occurrence of water hammer is 2×10^{-2}/per year (4×10^{-8} per minute), then the probability that it will occur during the exact minute that a seismic event (probability of 4×10^{-3}/year) is occurring is $4 \times 10^{-8} \times 4 \times 10^{-3} = 1.6 \times 10^{-10}$/year.

Standby systems such as ECCS, RCIC and AFW can be initiated as the result of a seismic event. Water hammer loads, however, generally can not occur until after the seismic event is over, for the reasons discussed below. The following sequence of events must occur to initiate a water hammer in these systems. First, the seismic event must cause damage resulting in loss of normal cooling water, such as feedwater. Then certain parameters must rise to a level that requires automatic or operator initiation of the standby equipment. The standby pump must be started and accelerate the water slug through a voided line segment. In the case of SGWH, several additional minutes are also required for the steam generator to lose level and for the sparger to drain. These steps take in excess of the typical 30 second duration during which seismic events have significant forces.

A possible exception is that of a large LOCA being initiated by a seismic event. Systems forming the reactor coolant boundary are designed for seismic events. The probability of seismic induced failure of an SSE designed system can be shown to be 2×10^{-6}/year (reference 9). Although large LOCAs only represent a small fraction of all system damage modes, it will be conservatively assumed that the probability of a seismic induced large LOCA is 2×10^{-6}/year. The frequency of water hammer in the RHR system, which can be used to mitigate a large LOCA, is 5.6×10^{-3}/demand. Using these values, the probability of a water hammer occurring simultaneously with a large LOCA can be conservatively calculated to be 1×10^{-8}/year. Therefore, the potential for water hammer occurring in a standby system as the result of a seismic event is very small.

Table 3-7
Frequency of Occurrence of Other Dynamic Loads In PWRS

System	Vibrational	SRV(1) Discharge /yr	Water Hammer/ Demand or year	Steam Hammer/ yr
Feedwater(2)	Constant	NA	$3.8x10^{-2}$/yr	NA
Reactor Coolant	Constant	See pressurizer	none reported	NA
Main steam	NA	6 - 8/yr	$1.7x10^{-2}$/yr	6 - 8/yr
Auxiliary Feedwater	1/demand	NA	$1.2x10^{-4}$/demand	NA
Residual Heat Removal	1/demand	NA	$1.7x10^{-4}$/demand	NA
Chemical and Volume Control	constant	NA	$3.5x10^{-3}$/yr	NA
ECCS Inject.	1/demand	NA	$2.9x10^{-4}$/demand	NA
Containment Spray	1/demand	NA	none reported	NA
Auxiliary Cooling Water	1/demand	NA	$7x10^{-3}$/yr	NA
Pressurizer	NA	3-5/yr	none reported	NA
Spent Fuel	1/demand	NA	none reported	NA
Steam Generator	NA	NA	$8.7x10^{-2}$/yr	NA

Footnotes:

1. Equipment relief valves having insignificant loads not included. Each SRV discharge event may consist of multiple valve actuation.

2. Excludes SGWH

Table 3-8
Frequency of Occurrence of Other Dynamic Loads in BWRS

System	Vibrational	SRV(1) Discharge /yr	Water Hammer/ Demand or year	Steam Hammer/ yr
Low Pressure				
Core spray	1/demand	NA	1.9x10^{-3}/demand	NA
Feedwater	1/demand	NA	1.7x10^{-2}/demand	
Residual Heat Removal	1/demand	NA	5.6x10^{-3}/demand	NA
High Pressure Coolant Injection (HPCI)	1/demand	NA	1.x10^{-2}/demand	NA
Reactor Core Isolation Cooling (RCIC)	1/demand	NA	8.7x10^{-4}/demand	NA
Main Steam	NA	7-9/yr	1.2x10^{-2}/yr	7-9/yr
Auxiliary Cooling Water	1/demand	NA	2.2x10^{-2}/yr	NA
Reactor Recirculation	constant (while pumps operational)	NA	none reported	NA
Standby Liquid Control	1/demand	NA	none reported	NA
Spent Fuel Pool Cooling	1/demand	NA	5.6x10^{-3}/yr	NA
Reactor Water Cleanup	NA	NA	5.6x10^{-3}/yr	NA
Control Rod Drive	1/demand	NA	7/yr	NA
Isolation	1/demand	NA	1.4x10^{-2}/demand	NA

Footnotes:

1. Equipment relief valves having insignificant loads not included. Each SRV discharge event may consist of multiple valve actuations and consecutive valve actuations.

3.5 Load Magnitude

The magnitudes of "other dynamic loads" cover a wide range and depend on many parameters. They vary from plant to plant as well as from system to system. Typical values for some of these loads and estimates of the effect of various parameters on the magnitude of these loads are presented below.

3.5.1 Anticipated Other Dynamic Loads

A conservative estimate of water hammer loads can be made by assuming the pipe to be rigid and the flow to stop instantly. The maximum pressure rise is the product of fluid density, wave velocity and the change in fluid velocity.

In those cases where the water hammer is caused by rapid valve closure,valve closure time has a significant effect on the water hammer load. The valve closure time is generally compared with the wave travel time (2L/a) where L is the distance the wave has to travel before it is reflected and a is the wave velocity. For instance, according to Reference 6, if the valve closure time is 3 times the wave travel time, then the actual pressure rise will be 30 - 40 percent of the theoretical maximum value.

Using the above method, steam-hammer loads caused by turbine stop valve closure can be estimated. For a main steamline with a flow area of 3. ft^2 and a flow-rate of 1000. lb/sec of saturated steam at 1000. psi, the theoretical pressure rise is about 140 psi, which produces an axial load of about 60. kips. A more detailed analysis, using the PRTHRUST computer program, (reference 11) which produced a force time history for each pipe segment, yielded a maximum peak load of approximately 40. kips.

Water hammer loads caused by check valve closure in the feedwater line are on the order of 50 kips. The magnitude of this load is very sensitive to how rapidly the check valve closes. Ideally, the check valve should start to close as soon as the flow stops. Any delay in closure will cause a substantial increase in the loads.

Control Rod Drive (CRD) hydraulic valves open in 10 - 60 ms and can create water hammers. Analyses, discussed in reference 12, report piping segment forces may reach 700 pounds and transient pressure peaks may reach 2800 psi. Both of those values are within the design capability of the piping system.

For an open discharge safety-relief valve with a flow-rate of 116.38 lb/sec, and a discharge line flow area of 50.03 in^2, reference 7 gives a thrust load of 12.8 kips. Because this load is almost directly proportional to the flow-rate, a reasonable estimate of loads for other flow-rates can be obtained by direct proportioning.

Estimating the SRV loads for BWR plants is more involved due to the complexity of the phenomena associated with a closed discharge system. The submerged portion of the discharge line contains a slug of water that has to be expelled before the air and then steam can be discharged. The water slug is rapidly accelerated and usually expelled in less than 0.5 seconds. When the slug makes a 90 degree turn in the discharge device (usually a sparger), it exerts a large axial force, on the order of 50 - 100 kips on the discharge line. This force is in the form of a sharp spike with a mean width of 20 - 30 msec.

The rest of the discharge line which is not submerged, experiences loads of much lower magnitude. These loads are caused by pressure waves introduced by the inflow of steam and reflected back and forth between the water slug interface and the SRV. To obtain an estimate of these loads, a simplified conservative method based on compressible fluid flow principles was used. Maximum forces were calculated for a range of valve capacities, discharge line sizes and steam pressures. The results are shown in table 3-9. The loads calculated are very conservative due to the assumption of instantaneous valve opening and not considering either steam condensation in the discharge line or pressure drop due to friction. For instance, a detailed analysis of case #2, using the method of characteristics (MOC) produced a maximum axial force of 7.7 kips compared with 16.5 kips calculated by this conservative method. The valve opening time used in the MOC analysis was .02 seconds. However, the results are useful for obtaining rough estimates of the magnitude of the SRV loads and the effects of various parameters. The results seem to be sensitive to steam flow-rate (valve capacity), but not to pipe size. The reason for the negligible effect of pipe size is the fact that pressure and velocity in the line decrease with increasing pipe size and this reduction cancels the increase in the pipe area, so that the resulting force does not change. The effect of steam pressure (upstream of the valve) is the same as the effect of flow-rate, because the flow-rate through the valve is proportional to the upstream stagnation pressure.

Table 3-9

Parametric Study on SRV Loads

Case #	Steam Pressure (PSIA)	Valve Capacity (lb/sec)	Flow Area (ft^2)	Max Force (Kips)
1	1000.	200.	.32	18.0
2	1000.	200.	.52	16.5
3	1000.	300.	.52	27.0
4	1000.	400.	.52	37.0
5	1000.	200.	.75	15.5
6	1000.	300.	.75	25.0
7	1000.	400.	.75	36.0
8	1150.	200.	.32	18.0
9	2000.	200.	.32	17.5
10	2000.	400.	.32	40.0

To summarize, water-hammer loads due to check valve closure in feedwater line are less than 50 kips and SRV loads range from several kips to about 100 kips for the submerged portion of closed discharge systems. Water hammer loads in CRD lines are about 700 pounds and the pressure peak as high as 2800 psi. Steam hammer loads due to TSV closure are less than 50 kips.

3.5.2 Unanticipated Water Hammers

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. Examples of unanticipated water hammer include those caused by steam bubble collapse, void filling and water entrainment in steam lines. Unanticipated water hammers generally involve bubble collapse, water entrainment or void filling. In all of these cases, a slug of water is accelerated through a void and is instantly stopped upon impact with a closed valve or a water filled section of piping.

Because of the number of variables involved, unanticipated water hammer loads can only be estimated through bounding analyses. The range of observed forces due to unanticipated water hammers is very large. Some events caused no visible damage while others caused considerable damage to the piping support systems, indicating that the forces exceeded the design basis of the system. For instance, steam generator water hammer (SGWH) can produce local pressures as high as 6000 psi. Such pressure spikes, however, are not propagated down the piping, because pressure is reduced by plastic deformation of the piping (bulging). A pressure rise of 2500 psi can be propagated through the piping, producing a 500 kips force in an 18 inch feedwater line.

3.6 Load Frequency Content

Dynamic response of piping systems to a forcing function depends on frequency content as well as the magnitude of the forcing function. This section presents estimates of the frequency content of water (steam) hammer and SRV loads. Flow-induced vibration frequencies are not discussed because FIV loads are not considered in the dynamic analysis of piping systems.

3.6.1 SRV Forcing Function

For open discharge SRV's an equivalent static analysis is usually performed and the time history of the load does not have much relevance. For the closed discharge SRV's, that discharge to a pool or tank of water, the loads typically resemble the one shown in figure 3-1, except for the submerged segment that experiences a different type of loading (see figure 3-2).

The first spike shown in figure 3-1 corresponds to the initial shock wave entering the segment and produces a positive force (opposite the flow direction). This spike is followed by a second spike which corresponds to the arrival of the steam-air interface. The negative spike which follows, is caused by the reflection of the wave after it reaches the air-water interface. It is followed by a positive spike denoting the arrival of the pressure wave at the upstream elbow of the segment. These two spikes have a frequency of about 30hz. The transient is essentially complete in less than 0.3 seconds. Most of the energy of the forcing function occurs at frequencies above 20 hz.

The submerged portion of the discharge line is generally attached to a discharge device such as a quencher (sparger) or a ramshead. As shown in figure 3-2, there is a positive force which increases until the water slug starts to leave the discharge line. Then a strong negative spike follows as the slug turns 90 degrees at the junction of the discharge device. The width of the negative spike is about .05 seconds. This forcing function has most of its energy above 10 hz.

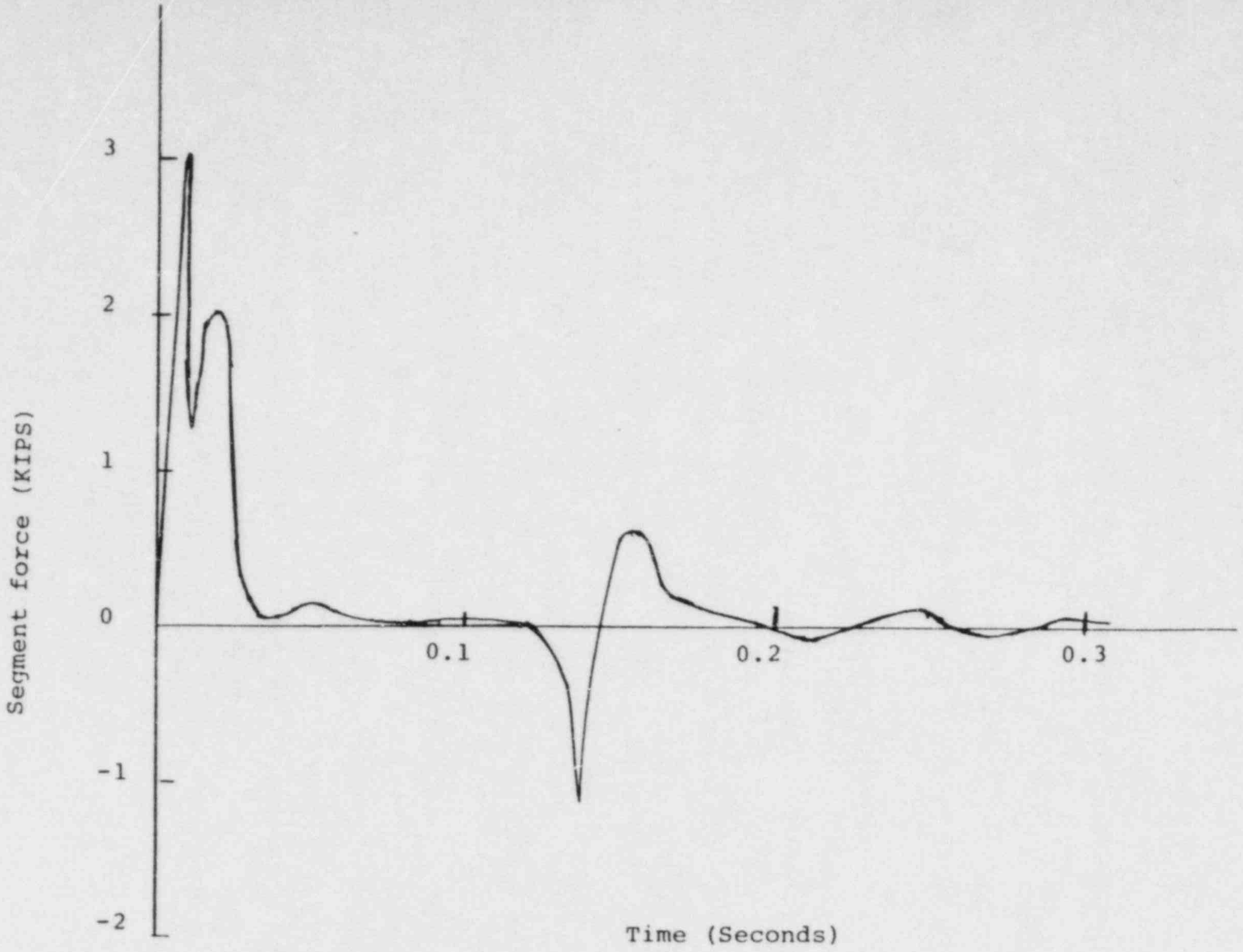

Figure 3-1. Typical SRV discharge line forcing function

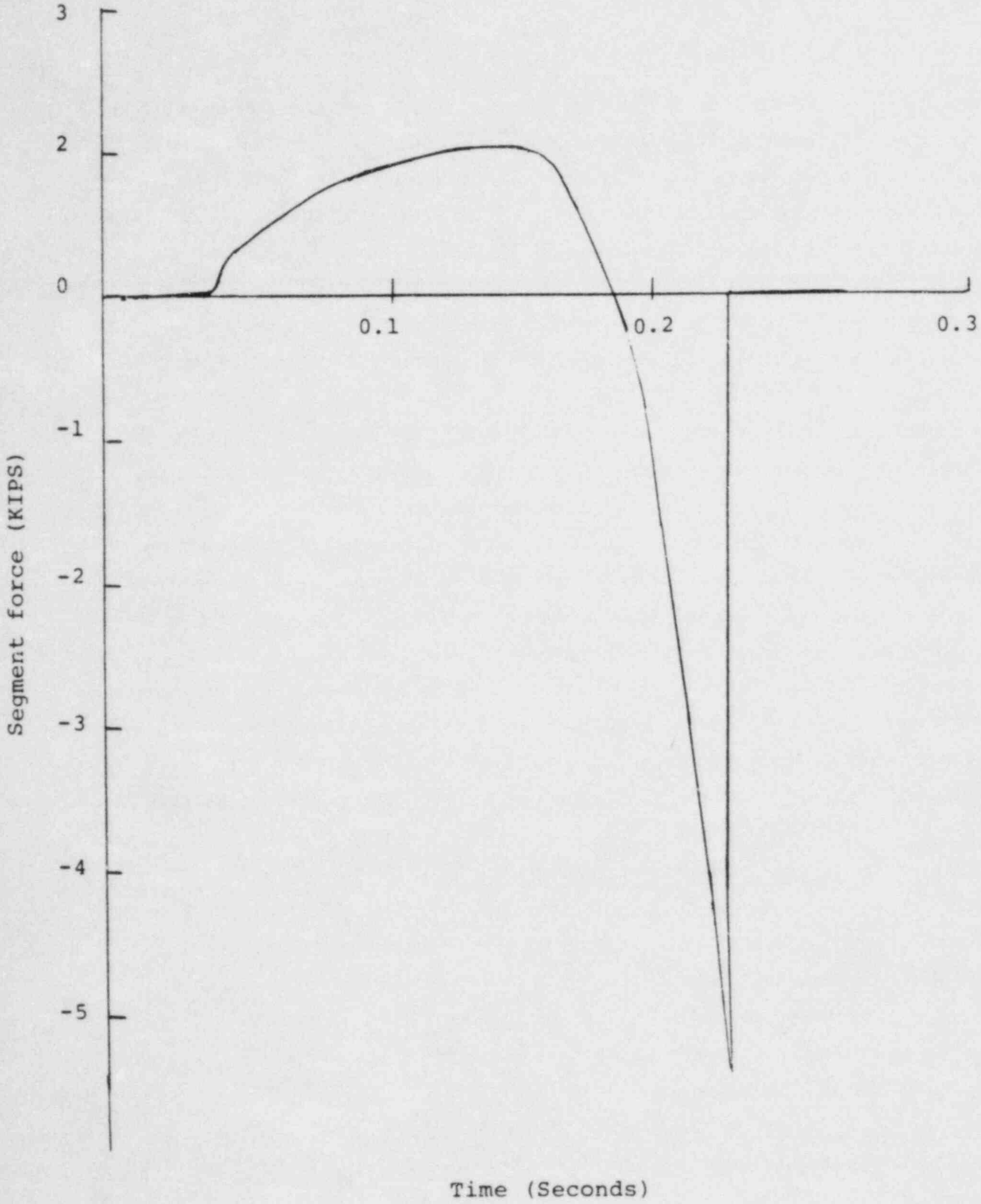

Figure 3-2. Typical SRV line submerged section forcing function

The frequency content of a forcing function can be obtained by performing a power spectral density (PSD) analysis of the function. A more meaningful method is to develop amplified response spectra (ARS) of the forcing function. PSD analysis provides the power of each harmonic, which is not necessarily a measure of the response of the system. The response depends on the number of cycles and the natural frequency of the system. ARS provides a good picture of how a system with a certain natural frequency and a certain damping factor will respond to the forcing function.

To illustrate this point, a typical SRV forcing function (figure 3-3) was analyzed. A 0.32 second segment of the forcing function was selected for both analyses. The results of the PSD analysis are shown in table 3-10, where PSD values are listed in descending order. The frequencies are multiples of 3.125 hz which corresponds to the length of time segment (.32 seconds). The table shows significant power at 3.125, 6.25, and 9.375 hz frequencies. However, the forcing function contains only 1, 2, and 3 cycles of these harmonics, respectively, not sufficient for a significant response. This fact is apparent in the results of the ARS analysis (figure 3-4), where the maximum response occurs at about 40 hz, and responses for the frequencies below 20 hz are less than one half of the maximum response.

3.6.2 Water (Steam) Hammer Forcing Function

The frequency content of water hammer forcing functions depend on:

- Wave speed in the pipe
- Total pipe length
- Segment length (between elbows)
- Location of the segment

To illustrate these points, consider segment #3 of the system shown in figure 3-5. At time zero, a sudden flow stoppage occurs at point A (the flow direction before the incident is from B to A). A pressure wave travels upstream and, after a time t_o reaches point B. The wave front creates an

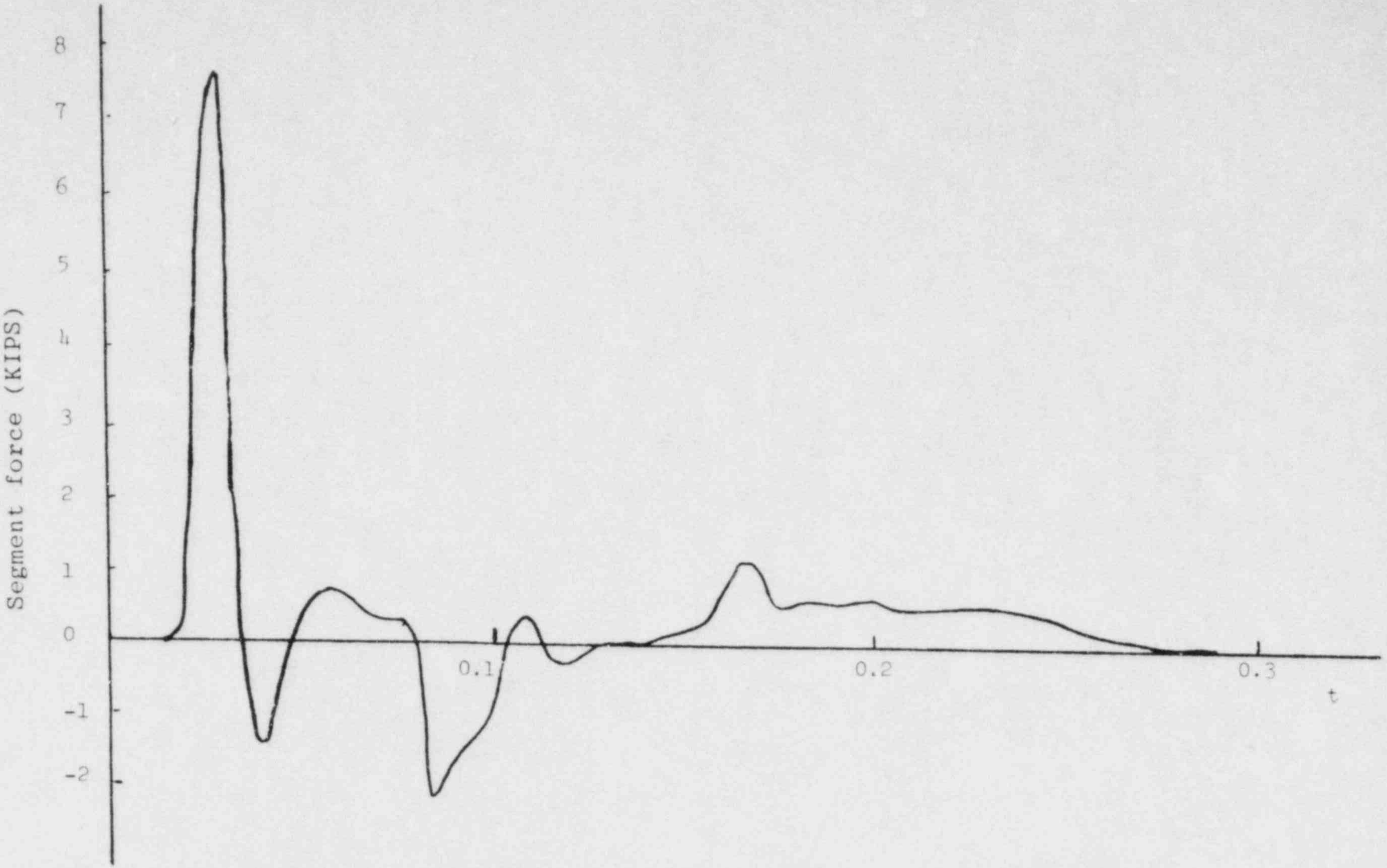

Figure 3-3. Forcing function (SRV)

Table 3-10

PSD Forcing Function of Fig. 3-3

FREQ (HZ)	PSD
6.250	0.6798D 05
21.875	0.6271D 05
25.000	0.5206D 05
28.125	0.3990D 05
37.500	0.3885D 05
40.625	0.3054D 05
34.375	0.2900D 05
9.375	0.2687D 05
43.750	0.2512D 05
18.750	0.2460D 05
3.125	0.2081D 05
50.000	0.1802D 05
31.250	0.1617D 05
59.375	0.1445D 05
46.875	0.1338D 05
12.500	0.1264D 05
56.250	0.1229D 05
62.500	0.1132D 05
53.125	0.1006D 05
65.625	0.8175D 04
15.625	0.6130D 04
78.125	0.4700D 04
75.000	0.3412D 04
71.875	0.3120D 04
81.250	0.2757D 04
68.750	0.1369D 04
93.750	0.7395D 03
90.625	0.5682D 03
84.375	0.4604D 03
96.875	0.2732D 03
87.500	0.1208D 03
0.000	0.1208D -20

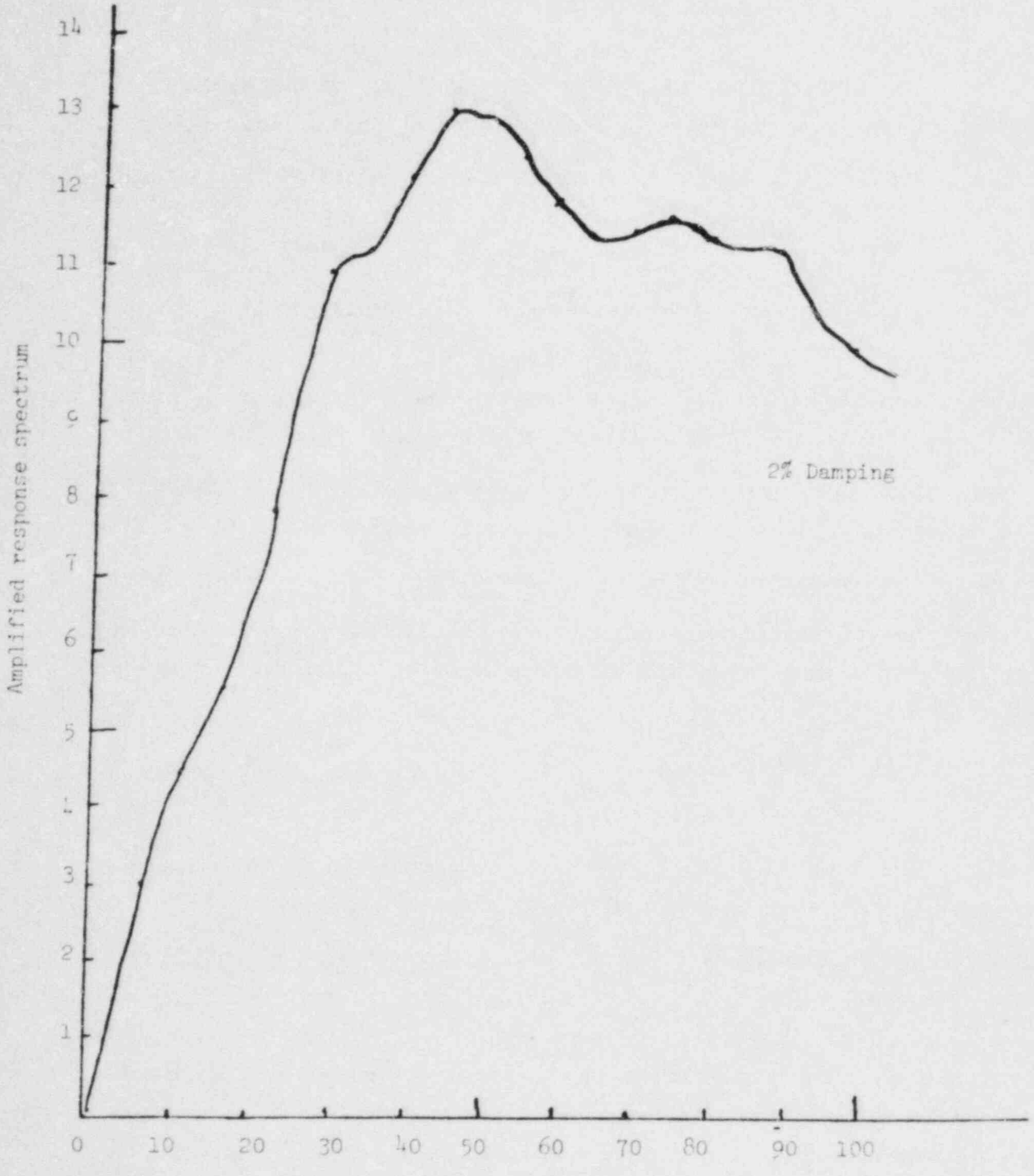

Figure 3-4. ARS for figure 3-3 forcing function

axial force in the original direction of flow (negative force) along the axis of segment #3 (see figure 3-6). The duration of this force, (t_1), is equal to the time it takes for the wave to travel the distance (L_1) from B to C:

$$t_1 = L_1/a, \text{ where } a = \text{wave velocity.}$$

Once the wave reaches point C, the pressure in segment #3 is uniform and the axial force vanishes. After a time t_2 a decompression wave, which is the reflection at point D, reaches point C creating a negative axial force equal to the first one. This force also lasts for t_1 seconds, which is the time it takes for the pressure wave to travel from C to B. At t_2 seconds after the appearance of the first negative force, a positive force is caused by the reflection and doubling of the decompression wave at point A. The time T is the period of the spikes:

$$T = 4L/a,$$

where L is the total length of the pipe. The positive force is repeated after t_2 seconds when a new compression wave arrives at point C. Theoretically, this sequence of events continues indefinitely with a period of T.

A more realistic forcing function is shown as a dotted curve (figure 3-6). This function differs from the theoretical one in several ways:

- o The magnitudes of the forces are lower mainly because in real life, flow stoppage does not happen instantly but takes a finite time.
- o The forcing function is smooth and does not contain step changes. This is also a result of the finite time it takes to stop the flow.
- o Events are slightly delayed. This is because the actual wave speed is lower than the theoretical one, due to pipe expansion and other factors such as presence of gas bubbles.

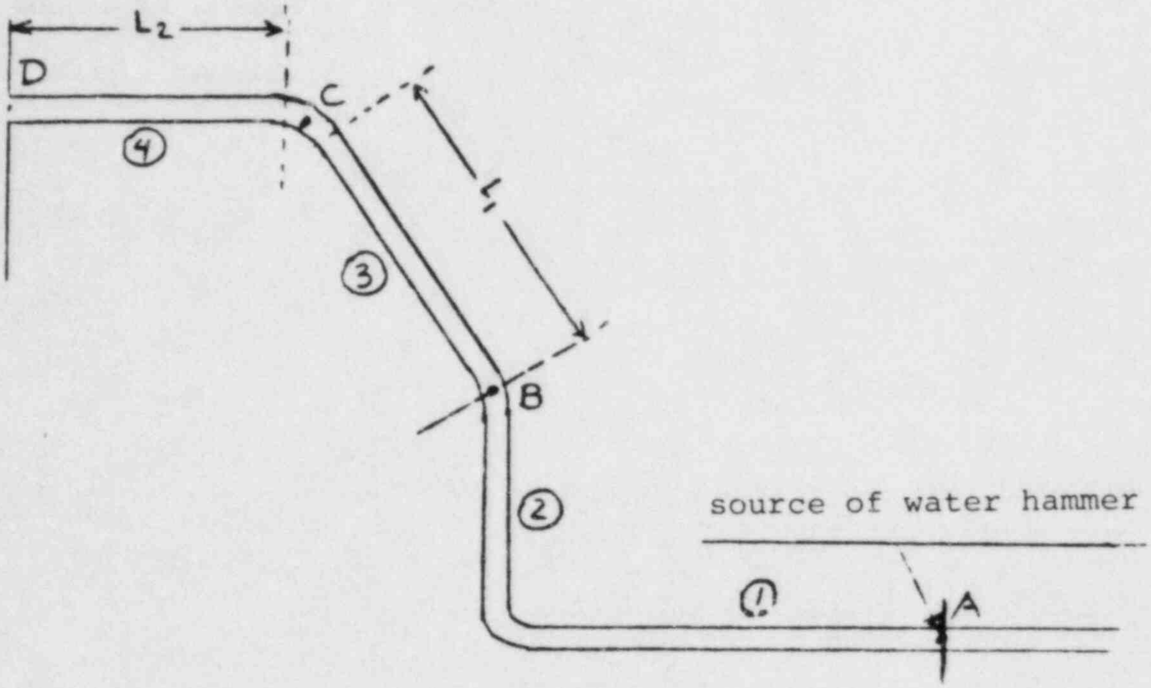

Figure 3-5. Piping arrangement

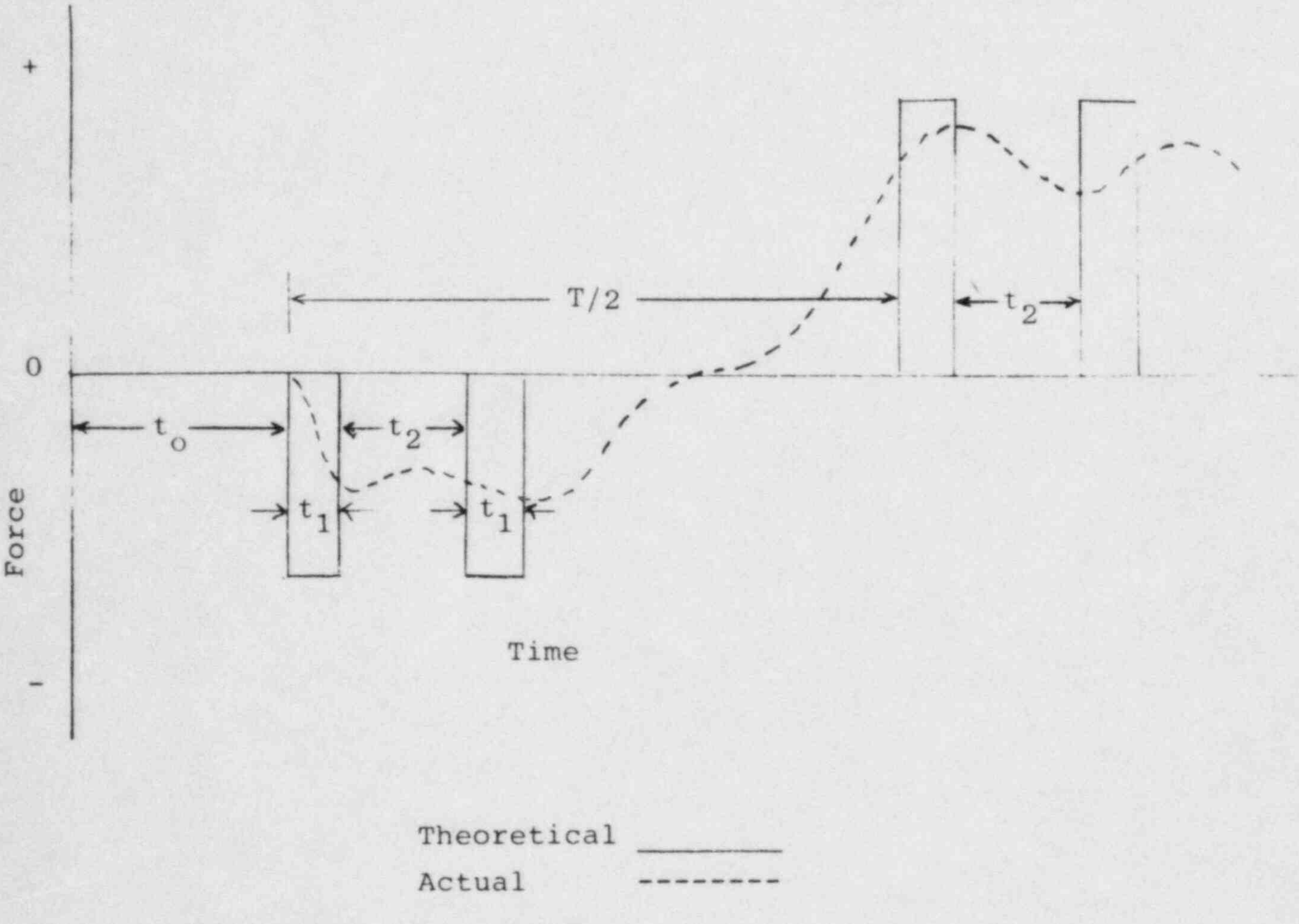

Figure 3-6. Theoretical and actual forcing functions

- The magnitudes of the forces decay rapidly because of various loss mechanisms such as mechanical and viscous forces.

A typical forcing function for steam hammer (turbine stop valve closure) is shown in figure 3-7. The first two negative spikes and a double positive spike can be seen. Notice the attenuation of the spikes which reduces the forcing function to a negligible level in about two seconds.

In summary, for pipe segments of 10 to 50 ft length, the width of the spikes will be approximately 2 to 15 ms for water hammer and 6 to 40 ms for steam hammer. The period T for a 200 ft length of piping is about .2 seconds for water-hammer and .5 seconds for steam-hammer.

3.6.3 Comparison of Frequency Content

SRV forcing function energy is mostly in 20Hz and higher frequencies. Because of the short duration of the forcing function, lower frequency components do not produce a significant response. Water hammer forcing functions for piping systems of 100 - 400 ft. length will have a 2 - 10 Hz component, corresponding to (a/4L) of the system, and an 80 - 400 Hz component corresponding to segment lengths (10 - 50 ft). Similarly, steam hammer forcing functions contain a 1 - 4 Hz component and a 20 - 100 Hz harmonic. All the above forcing functions will contain many frequency components within the given ranges. For this reason and the fact that each segment will have its unique forcing function, the response of a piping system cannot be estimated without a detailed dynamic analysis of the system.

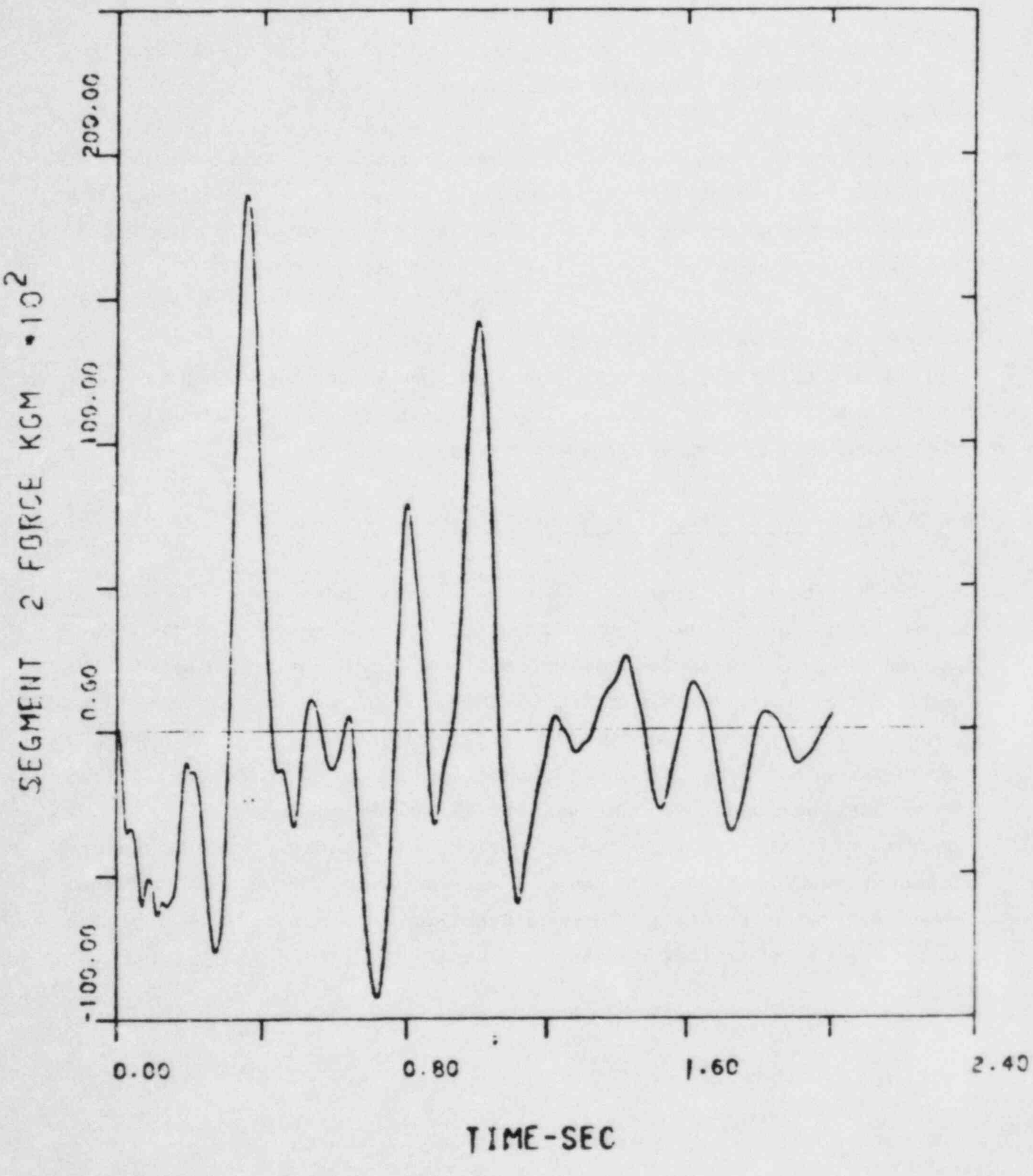

Figure 3-7. Typical forcing function for TSV closure

4.0 SIGNIFICANT FINDINGS

4.1 General Requirements

Section III of ASME code and section 3.9.3 of the NRC SRP specify SRV loads and loads due to flow transients (water hammer and steam hammer) as loads that must be considered in the design of piping systems. Section 3.9.3 of SRP specifies the manner in which SRV loads must be combined with sustained loads and seismic loads and the corresponding service stress limit. The rules and requirements for addressing these dynamic loads are clear and adequate. The application of these rules, however, require multidisciplinary expertise and is sometimes influenced by engineering judgement.

Design specifications for safety-related systems which are susceptible to "other dynamic loads" should include sufficient information on various anticipated transients and their timing in relation to other events to ensure their consideration in the design process. The possibility of event occurrence and effects caused by the following conditions should be considered for safety related systems:

- Column separation, void or bubble formation; cavitation, slug formation and bubble collapse.
- Sudden changes in the flow-rate.
- Flashing due to pressure drop.
- Sudden pressure drop due to steam quenching.
- Intermittent operation.

4.2 Flow Induced Vibration Loads

FIV loads are not included in piping analyses. However, plant systems are tested for FIV during preoperational and hot functional testing. Design modifications are implemented to correct FIV when needed. Not combining FIV loads with other loads is appropriate because FIV loads are small in magnitude when the system is correctly designed and installed. The effect of not correcting large FIV loads is fatigue failure because of the many load cycles that would occur during a systems operational life.

4.3 SRV Discharge Loads

Significant SRV loads are currently included in piping design bases. Small valves on equipment will not affect lines nor will small equipment (process heat exchanger) relief valves placed on attaching lines, because the valves are very small with respect to line size. Main steam line and PWR pressurizer SRV loads are significant and are included in the design bases of piping.

Reviews of analytical results show that SRV loads in the valve discharge lines are significantly larger than seismic and other loads in all directions and are thus the dominant factor in controlling the design of the valve discharge piping support systems. SRV loads transmitted to the lines on which they are mounted, such as main steam lines, are the controlling load along the axis of the valve. However, the effects of SRV loads on their source line are not significant in other directions. Changing seismic design criteria will not affect or change the effects of SRV loads on either SRV lines or the lines upon which the SRVs are mounted, provided that SRV loads are accounted for in accordance with current requirements.

Actuation of SRVs can result from a seismic event and can occur while the seismic event is in progress. Therefore, it is appropriate to combine SRV loads with seismic loads and continual piping loads such as pressure, thermal, and deadweight. The SRV loads should be combined using square root sum of the squares (SRSS) rather than absolute summing, because the probability of peak seismic and SRV loads occurring simultaneously is low. Both loads have distinct short duration (milliseconds) peaks that are distinctly higher than other portions of the load time history. The loads have different frequency content, duration and initiation times. Thus the use of SRSS rather than absolute sum combinations of SRV and seismic loads is appropriate.

4.4 Anticipated Water (Steam) Hammer Loads

Anticipated water (steam) hammers, that are generally included in piping support system design, are steam hammers induced by turbine stop valve (TSV) closure, and water hammers caused by the trip and restart of open loop safety related service water pump, control rod drive (CRD) insertion and feedwater check valve closure. These water (steam) hammers should be considered, because they occur when components such as check valves, TSVs and CRDs perform their intended function. TSV and CRD actuation occur frequently enough to require their inclusion. Pump trips are also a frequent enough occurrence to require consideration. The automatic restart of a safety related pump is a result of a component performing its intended function.

The closure or opening of valves in most systems do not result in significant water hammers because their closure times (5 to 120 seconds) is orders of magnitude longer than the sonic transit times (≈ .1 seconds) of the system's lines. An exception to this are the turbine stop valves that close in 0.1 seconds. Because of the low density and sonic velocity of steam, TSV loads are much smaller than those in a water filled line. Except for TSV closure and CRD insertion, measurable loads from normal valve opening or closing have never been significant enough to be noted in nuclear power plants.

Although pump trip is a common occurrence in power plants, pump trip induced water hammers have not been reported in nuclear power plants. This is because pump coastdown times (2 to 5 seconds) are long with respect to piping sonic transit times. A potential exception is open loop service water systems. Water lines run from the ultimate heat sink to the plant and may be several thousand feet long. Additionally, the service water lines discharge at a low elevation at ambient pressure. These design features can make the high points of open loop service water systems subject to column separation and drainage caused voiding. Although such events have not occurred during plant operation, analysis and preoperational testing has shown that water hammer caused by pump trip in an open loop service water system is possible. Therefore, essential water hammer loads should be included in the design basis of service water systems, if these occurrences are possible.

Anticipated water (steam) hammer loads should be combined with seismic loads because the events causing these loads can be initiated by a seismic events. Seismic and water hammer loads should be combined using SRSS rather than absolute summing for the reasons discussed below. The duration and initiation time of water hammer and seismic loads are different. Seismic loads have a short (milliseconds) distinct peak that is significantly higher than other portions of the load. Individual piping segments only have peak response to water hammer loads for intermittent short (millisecond) periods. Therefore, the probability of seismic and water hammer peak loads occurring simultaneously is very low and it is appropriate to sum these loads using SRSS methodology.

4.5 Unanticipated Water Hammers

Unanticipated water hammers are generally not included in the design basis of piping support systems. Unanticipated water hammers need not be included in the design basis of piping support systems for several reasons including:

- Frequency of occurrence

- Effect on piping and plant safety
- Effect of designing supports for loads

Tables 3-7 and 3-8 show that unanticipated water hammers occur far less frequently than other events such as TSVC induced steam hammer, SRV discharge and vibration.

Analyses reported in references 10 and 13 showed that water hammer had no calculated effect on public risk in PWRs and BWR-3s, and an insignificant effect on public risk in BWR-4s. The analyses of BWR-4 water hammer included many events that occurred at the initiation of the BWR-4 design. The frequency of water hammer occurrence in BWR-4s has been significantly reduced by the incorporation of design changes such as keep full systems, vacuum breakers, and improved valve controls, as well as increased operating experience. Furthermore, the few adverse effects on system operability were caused by component damage, such as blown turbine rupture disc's and not by piping failures. There were no incidents in which the reactor pressure boundary integrity was failed or in which damage to a safety related line resulted in the failure of a safety related component or system. Therefore, including unanticipated water hammers in the design basis of piping would not have affected plant safety. Most of the BWR-4 water hammers occurred during testing of ECCS systems and if a failure had occurred, it would not have had any adverse results unless, there was a need for the ECCS system following testing coupled with another ECCS failure.

Consideration must be given to the magnitude of water hammer forces in evaluating the methods of mitigating water hammer loads. Forces from unanticipated water hammers have been so low in some cases that no visible damage has been noted. In other cases, piping supports, including snubbers, have been severely damaged by unanticipated water hammers, indicating that the water hammer forces far exceeded the forces for which the piping support system was designed. Water hammer forces can be propagated through piping with little attenuation except at branches. Therefore, a support system that would accommodate large water hammer loads would require installing very large supports at almost every piping segment. Such supports would make the piping system unnecessarily stiff and would create considerable access and inspection problems. As an example, to design for SGWH loads of ~500 kips, would require the addition of massive pipe supports and strengthening of support and building structures. The installation of such devices to partially mitigate events of low frequency of occurrence that have not had a significant effect on plant safety would reduce rather than increase plant safety. It is therefore concluded, that while efforts to reduce the incidence of unanticipated water hammers should continue, including loads from unanticipated water hammers in the design basis of piping support systems is not warranted. Efforts to minimize the occurrence of water hammers through proper design and operational considerations and operator training should continue.

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This report presents the results of an evaluation performed to determine current and recommended practices regarding the consideration of water hammer flow-induced vibration and safety-relief valve loads in the design of nuclear power plant piping systems. Current practices were determined by a survey of industry experts. Recommended practices were determined by evaluating factors such as load magnitude and frequency content, system susceptibility to loads, frequency of load occurrence and safety effects of postulated piping damage.

This report was prepared for use by the NRC staff in developing positions regarding consideration of dynamic piping loads for use by the NRC's Piping Review Committee.

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